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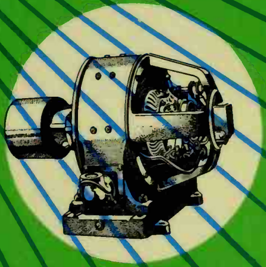

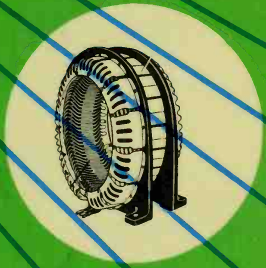

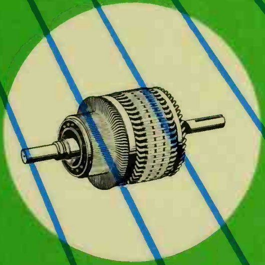

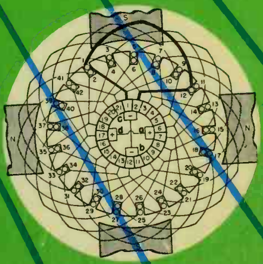

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PREFACE

Basic Electricity is written primarily to provide coverage of the electrical knowledge factors required of men of the U. S. Navy and Naval Reserve who desire to advance in certain ratings. The REQUIREMENTS FOR ADVANCEMENT for each rating specify the exact electrical knowledge factors required in each case. Some ratings require a much broader and more thorough coverage of electricity than others. For this reason, *Basic Electricity* is written to provide either the broad or the more limited knowledge of electrical fundamentals, depending on which chapters of the text are studied. To provide this type of coverage, the text is written in two main parts—Part 1 and Part 2.

Part 1 provides the more limited coverage of electrical theory. Starting with the fundamental electrical nature of matter, it goes on to cover such subjects as the production of a voltage by various methods, the characteristics of simple electric circuits, magnetism, and the solving of problems in simple direct-current circuits. It also contains an introduction to fundamental alternating-current electricity, and a discussion of the effects of capacitance and inductance in electric circuits. The final chapter in Part 1 covers the basic indicating instruments commonly used to measure electrical voltage, current flow, resistance, and power. (NOTE: When you are going to study only the material in Part 1, you should also read chapters 20 and 21 in Part 2.) Chapter 20 covers electrical drawings and technical manuals, and chapter 21 is on safety.

Part 2 is written for the student who is held responsible for more difficult knowledge factors than those covered in Part 1. It also serves to provide material for the student who is interested in studying more difficult subject matter not actually required of him. In Part 2, the general theories of electricity studied in Part 1 are applied to electrical machines, such as generators, motors, transformers, and magnetic amplifiers. Also, more complicated instruments, synchros, and servomechanisms are discussed. The final chapters of the text cover electrical blueprints and wiring diagrams, and safety.

As one of the Navy Training Courses, this book was prepared by the U. S. Navy Training Publications Center for the Bureau of Naval Personnel.

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BASIC ELECTRICITY

PART 1

CHAPTER 1

FUNDAMENTAL CONCEPTS OF ELECTRICITY

What is Electricity?

The word ''electric'' is actually a Greek-derived word meaning AMBER. Amber is a translucent (semitransparent) yellowish mineral, which, in the natural form, is composed of fossilized resin. The ancient Greeks used the words ''electric force'' in referring to the mysterious forces of attraction and repulsion exhibited by amber when it was rubbed with a cloth. They did not understand the fundamental nature of this force. They could not answer the seemingly simple question, ''What is electricity?''. This question is still unanswered. Though you might define electricity as ''that force which moves electrons,'' this would be the same as defining an engine as ''that force which moves an automobile.'' You would have described the effect, not the force.

We presently know little more than the ancient Greeks knew about the fundamental nature of electricity, but tremendous strides have been made in harnessing and using it. Elaborate theories concerning the nature and behavior of electricity have been advanced, and have gained wide acceptance because of their apparent truth and demonstrated workability.

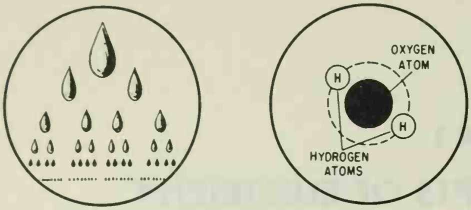
From time to time various scientists have found that electricity seems to behave in a constant and predictable manner in given situations, or when subjected to given conditions. These scientists, such as Faraday, Ohm, Lenz, and Kirchhoff, to name only a few, observed and described the predictable characteristics of electricity and electric current in the form of certain rules. These rules are often referred to as ''laws.'' Thus, though electricity itself has never been clearly defined, its predictable nature and easily used form of energy has made it one of the most widely used power sources in modern time. By learning the rules, or laws, applying to the behavior of electricity, and by learning the methods of producing, controlling, and using it, you will have ''learned'' electricity without ever having determined its fundamental identity.

THE MOLECULE

One of the oldest, and probably the most generally accepted, theories concerning electric current flow is that it is comprised of moving electrons. This is the ELECTRON THEORY. Electrons are extremely tiny parts, or particles, of matter. To study the electron, you must therefore study the structural nature of matter itself. (Anything having mass and inertia, and which occupies any amount of space, is composed of matter.) To study the fundamental structure or composition of any type of matter, it must be reduced to its fundamental fractions. Assume the drop of water in figure 1-1 (A) was halved again and again. By continuing the process long enough, you would eventually obtain the smallest particle of water possible—the molecule. All molecules are composed of atoms.

A molecule of water (H_2O) is composed of one atom of oxygen and two atoms of hydrogen, as represented in figure 1-1 (B). If the molecule of water were further subdivided, there would remain only unrelated atoms of oxygen and hydrogen, and the water would no longer exist as such. This example illustrates the following fact—the molecule is the smallest particle to which a substance can be reduced and still be called by the same name. This applies to all substances—liquids, solids, and gases.

When whole molecules are combined or separated from one another, the change is generally referred to as a PHYSICAL change. In a CHEMICAL change the molecules of the



DIVIDING A DROP OF WATER

(A)

MOLECULE OF WATER H_2O

(B)

Figure 1-1.—Matter is made up of molecules.

substance are altered such that new molecules result. Most chemical changes involve positive and negative ions and thus are electrical in nature. All matter is said to be essentially electrical in nature.

THE ATOM

In the study of chemistry it soon becomes apparent that the molecule is far from being the ultimate particle into which matter may be subdivided. The salt molecule may be decomposed into radically different substances—sodium and chlorine. These particles that make up molecules can be isolated and studied separately. They are called ATOMS.

The atom is the smallest particle that makes up that type of material called an ELEMENT. The element retains its characteristics when subdivided into atoms. More than 100 elements have been identified. They can be arranged into a table of increasing weight, and can be grouped into families of material having similar properties. This arrangement is called the PERIODIC TABLE OF THE ELEMENTS.

The idea that all matter is composed of atoms dates back more than 2,000 years to the Greeks. Many centuries passed before the study of matter proved that the basic idea of atomic structure was correct. Physicists have explored the interior of the atom and discovered many subdivisions in it. The core of the atom is called the NUCLEUS. Most of the mass of the atom is concentrated in the nucleus. It is comparable to the sun in the solar system, around which the planets revolve. The nucleus contains PROTONS (positively charged particles) and NEUTRONS which are electrically neutral.

Most of the weight of the atom is in the protons and neutrons of the nucleus. Whirling around the nucleus are one or more smaller particles of negative electric charge. THESE ARE THE ELECTRONS. Normally there is one proton for each electron in the entire atom so that the net positive charge of the nucleus is balanced by the net negative charge of the electrons whirling around the nucleus. THUS THE ATOM IS ELECTRICALLY NEUTRAL.

The electrons do not fall into the nucleus even though they are attracted strongly to it. Their motion prevents it, as the planets are prevented from falling into the sun because of their centrifugal force of revolution.

The number of protons, which is usually the same as the number of electrons, determines the kind of element in question. Figure 1-2 shows a simplified picture of several atoms of different materials based on the conception of planetary electrons describing orbits about the nucleus. For example, hydrogen has a nucleus consisting of 1 proton, around which rotates 1 electron. The helium atom has a nucleus containing 2 protons and 2 neutrons with 2 electrons encircling the nucleus. Near the other extreme of the list of elements is curium (not shown in the figure), an element discovered in the 1940's, which has 96 protons and 96 electrons in each atom.

The *Periodic Table of the Elements* is an orderly arrangement of the elements in ascending atomic number (number of planetary electrons) and also in atomic weight (number of protons and neutrons in the nucleus). The various kinds of atoms have distinct masses or

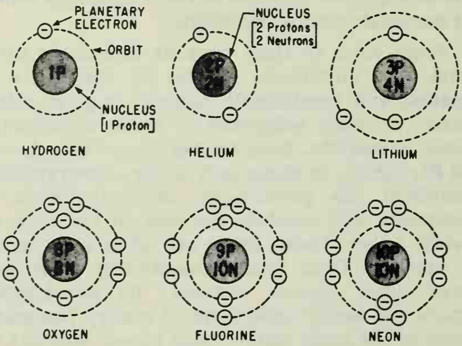


Figure 1-2.—Atomic structure of elements.

weights with respect to each other. The element most closely approaching unity (meaning 1) is hydrogen whose atomic weight is 1.008 as compared with oxygen whose atomic weight is 16. Helium has an atomic weight of approximately 4, lithium 7, fluorine 19, and neon 20, as shown in figure 1-2.

Figure 1-3 is a pictorial summation of the discussion that has just been presented. Visible matter, at the left of the figure, is broken down first to one of its basic molecules, then to one of the molecule's atoms. The atom is then further reduced to its subatomic particles—the protons, neutrons, and electrons. Subatomic particles are electric in nature. That is, they are the particles of matter most affected by an electric force. Whereas the whole molecule or a whole atom is electrically neutral, most subatomic particles are not neutral (with the exception of the neutron). Protons are inherently positive, and electrons are inherently negative. It is these inherent characteristics which make subatomic particles sensitive to electric force.

When an electric force is applied to a conducting medium, such as copper wire, electrons in the outer orbits of the copper atoms are forced out of orbit and impelled along the wire. The direction of electron movement is determined by the direction of the impelling force. The protons do not move, mainly because they are extremely heavy. The proton of the lightest element, hydrogen, is approximately 1,850 times as heavy as an electron. Thus, it is the relatively light electron that is most readily moved by electricity.

When an orbital electron is removed from an atom it is called a FREE ELECTRON. Some of the electrons of certain metallic atoms are so loosely bound to the nucleus that they are comparatively free to move from atom to atom.

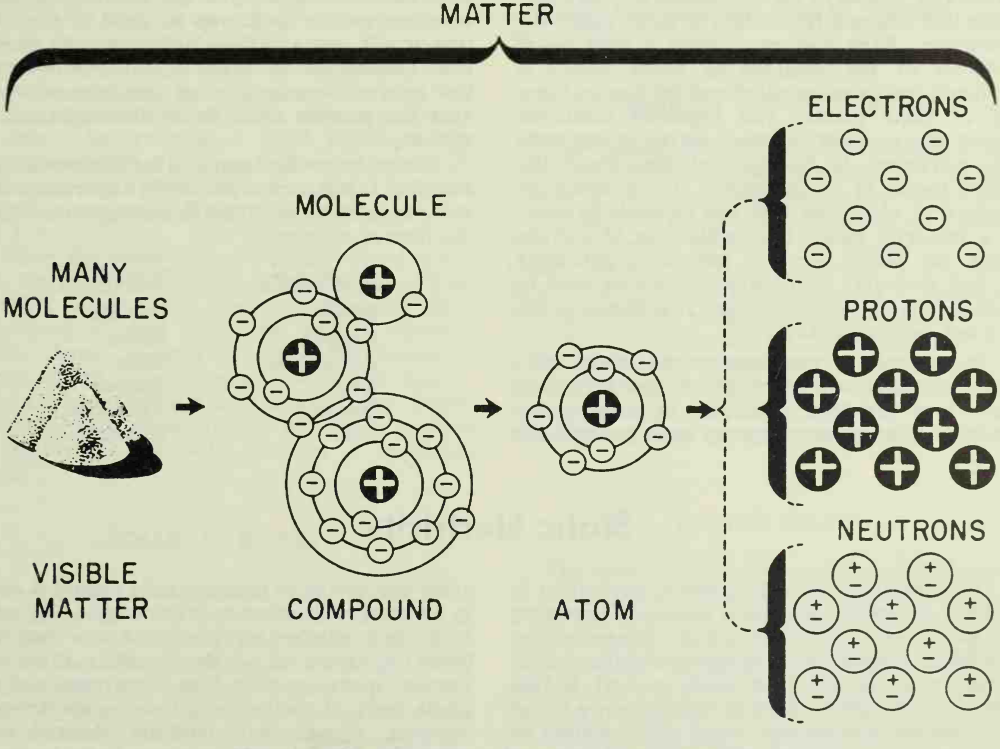


Figure 1-3.—Breakdown of visible matter to electric particles.

Thus, a very small force or amount of energy will cause such electrons to be removed from the atom and become free electrons. It is these free electrons that constitute the flow of an electric current in electrical conductors.

If the internal energy of an atom is raised above its normal state, the atom is said to be EXCITED. Excitation may be produced by causing the atoms to collide with particles that are impelled by an electric force. In this way, energy is transferred from the electric source to the atom. The excess energy absorbed by an atom may become sufficient to cause loosely bound outer electrons to leave the atom against the force that acts to hold them within. An atom that has thus lost or gained one or more electrons is said to be IONIZED. If the atom loses electrons it becomes positively charged and is referred to as a POSITIVE ION. Conversely, if the atom gains electrons, it becomes negatively charged and is referred to as a NEGATIVE ION. Actually then, an ion is a small particle of matter having a positive or negative charge.

Conductors and Insulators

Substances that permit the free motion of a large number of electrons are called CONDUCTORS. Copper wire is considered a good conductor because it has many free electrons. Electrical energy is transferred through conductors by means of the movement of free electrons that migrate from atom to atom inside the conductor. Each electron moves a very short distance to the neighboring atom where it replaces one or more electrons by forcing them out of their orbits. The replaced electrons repeat the process in other nearby atoms until the movement is transmitted throughout the entire length of the conductor. The greater the number of electrons that can be made to move in a material under the application of a given force the better are the conductive qualities of that material. A good conductor is said to have a low opposition or low resistance to the current (electron) flow.

In contrast to good conductors, some substances such as rubber, glass, and dry wood have very few free electrons. In these materials large amounts of energy must be expended in order to break the electrons loose from the influence of the nucleus. Substances containing very few free electrons are called POOR CONDUCTORS, NONCONDUCTORS, or INSULATORS. Actually, there is no sharp dividing line between conductors and insulators, since electron motion is known to exist to some extent in all matter. Electricians simply use the best conductors as wires to carry current and the poorest conductors as insulators to prevent the current from being diverted from the wires.

Listed below are some of the best conductors and best insulators arranged in accordance with their respective abilities to conduct or to resist the flow of electrons.

Conductors	Insulators
Silver	Dry air
Copper	Glass
Aluminum	Mica
Zinc	Rubber
Brass	Asbestos
Iron	Bakelite

Static Electricity

In a natural, or neutral state, each atom in a body of matter will have the proper number of electrons in orbit around it. Consequently, the whole body of matter comprised of the neutral atoms will also be electrically neutral. In this state, it is said to have a ''zero charge,'' and will neither attract nor repel other matter in its vicinity. Electrons will neither leave nor enter the neutrally charged body should it come in contact with other neutral bodies. If, however, any number of electrons are removed from the atoms of a body of matter, there will remain more protons than electrons, and the whole body of matter will become electrically positive. Should the positively charged body come in contact with another body having a normal charge, or having a negative (too many electrons) charge, an electric current will flow between them. Electrons will leave the more negative body and enter the positive body. This electron flow will continue until both bodies have equal charges.

When two bodies of matter have unequal charges, and are near one another, an electric force is exerted between them because of their unequal charges. However, since they are not in contact, their charges cannot equalize. The existence of such an electric force, where current cannot flow, is referred to as static electricity. ''Static'' means ''not moving.'' This is also referred to as an ELECTROSTATIC FORCE.

One of the easiest ways to create a static charge is by the friction method. With the friction method, two pieces of matter are rubbed together and electrons are ''wiped off'' one onto the other. If materials that are good conductors are used, it is quite difficult to obtain a detectable charge on either. The reason for this is that equalizing currents will flow easily in and between the conducting materials. These currents equalize the charges almost as fast as they are created. A static charge is easier to obtain by rubbing a hard nonconducting material against a soft, or fluffy, nonconductor. Electrons are rubbed off one material and onto the other material. This is illustrated in figure 1-4.

When the hard rubber rod is rubbed in the fur, the rod accumulates electrons. Since both fur and rubber are poor conductors, little equalizing current can flow, and an electrostatic charge is built up. When the charge is great enough, equalizing currents will flow in spite of the material's poor conductivity. These currents will cause visible sparks, if viewed in darkness, and will produce a crackling sound.

CHARGED BODIES

One of the fundamental laws of electricity is that LIKE CHARGES REPEL EACH OTHER and UNLIKE CHARGES ATTRACT EACH OTHER. A positive charge and negative charge, being unlike, tend to move toward each other. In the atom the negative electrons are drawn toward the positive protons in the nucleus. This attractive force is balanced by the electron's centrifugal force caused by its rotation about the nucleus. As a result, the electrons remain in orbit and are not drawn into the nucleus. Electrons repel each other because of their like negative charges, and protons repel each other because of their like positive charges.

The law of charged bodies may be demonstrated by a simple experiment. Two pith (paper pulp) balls are suspended near one another by threads, as shown in figure 1-5.

If the hard rubber rod is rubbed to give it a negative charge, and then held against the right-hand ball in part (A), the rod will impart a negative charge to the ball. The right-hand ball will be charged negative with respect to the left-hand ball. When released, the two balls will be drawn together, as shown in figure 1-5 (A). They will touch and remain in contact until the left-hand ball acquires a portion of the negative charge of the right-hand ball, at which time they will swing apart as shown in figure 1-5 (C). If positive charges are placed on both balls (fig. 1-5 (B)), the balls will also be repelled from each other.

COULOMB'S LAW OF CHARGES

The amount of attracting or repelling force which acts between two electrically charged bodies in free space depends on two things—(1) their charges, and (2) the distance between them. The relationship of charge and distance to electrostatic force was first discovered and written by a French scientist named Charles A. Coulomb. Coulomb's Law states that CHARGED BODIES ATTRACT OR REPEL EACH OTHER WITH A FORCE THAT IS DIRECTLY PROPORTIONAL TO THE PRODUCT OF THEIR CHARGES, AND IS INVERSELY PROPORTIONAL TO THE SQUARE OF THE DISTANCE BETWEEN THEM.

ELECTRIC FIELDS

The space between and around charged bodies in which their influence is felt is called an ELECTRIC FIELD OF FORCE. The electric field is always terminated on material objects and extends between positive and negative charges. It can exist in air, glass, paper, or a vacuum. ELECTROSTATIC FIELDS and DIELECTRIC FIELDS are other names used to refer to this region of force.

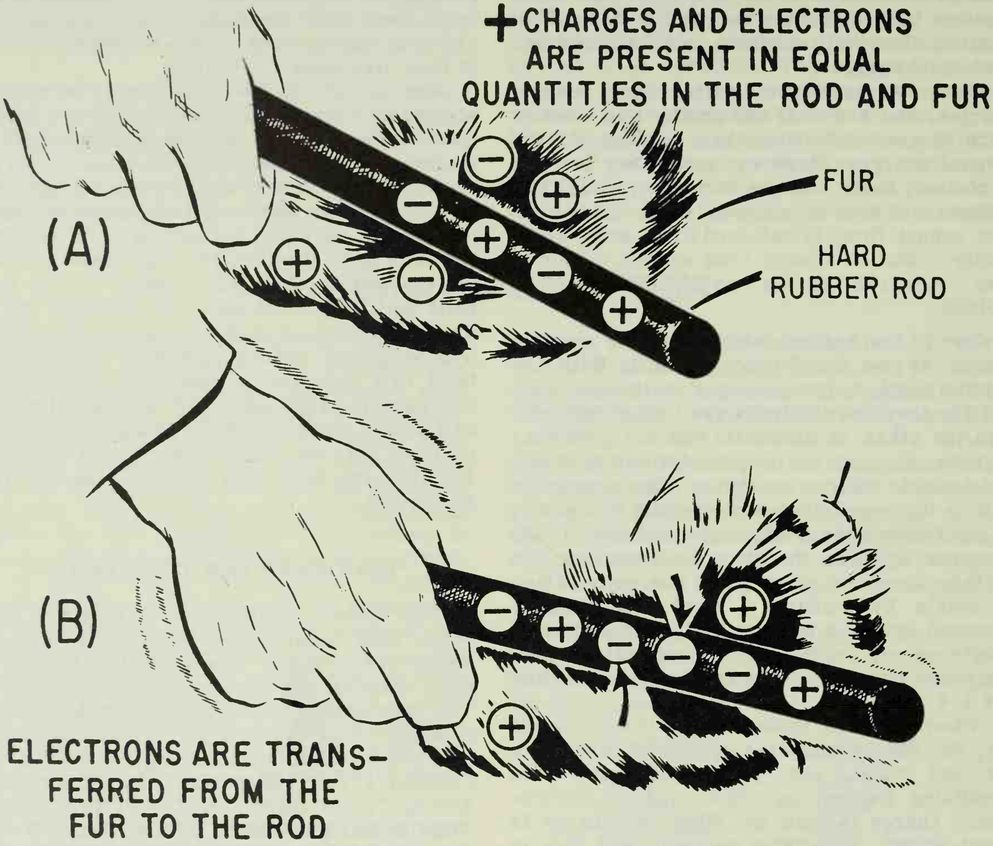

+CHARGES AND ELECTRONS ARE PRESENT IN EQUAL QUANTITIES IN THE ROD AND FUR
FUR
HARD RUBBER ROD
(A)
(B)
ELECTRONS ARE TRANSFERRED FROM THE FUR TO THE ROD

Figure 1-4.—Producing static electricity by friction.

Fields of force spread out in the space surrounding their point of origin and, in general, DIMINISH IN PROPORTION TO THE SQUARE OF THE DISTANCE FROM THEIR SOURCE.

The field about a charged body is generally represented by lines which are referred to as ELECTROSTATIC LINES OF FORCE. These lines are imaginary and are used merely to represent the direction and strength of the field. To avoid confusion, the lines of force exerted by a positive charge are always shown leaving the charge, and for a negative charge they are shown as entering. Figure 1-6 illustrates the use of lines to represent the field about charged bodies.

Figure 1-6 (A) represents the repulsion of like-charged bodies and their associated fields. Part (B) represents the attraction between unlike-charged bodies and their associated fields.

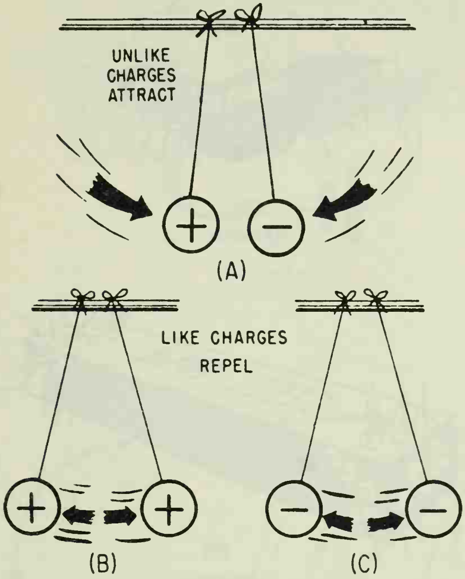


Figure 1-5.—Reaction between charged bodies.

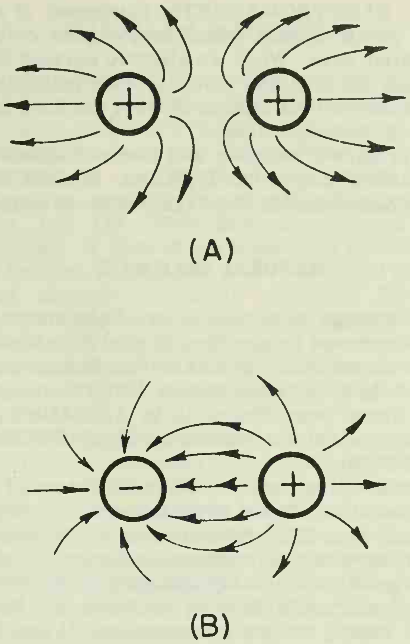


Figure 1-6.—Electrostatic lines of force.

Magnetism

A substance is said to be a magnet if it has the property of magnetism—that is, if it has the power to attract such substances as iron, steel, nickel, or cobalt, which are known as MAGNETIC MATERIALS. A steel knitting needle, magnetized by a method to be described later, exhibits two points of maximum attraction (one at each end) and no attraction at its center. The points of maximum attraction are called MAGNETIC POLES. All magnets have at least two poles. If the needle is suspended by its middle so that it rotates freely in a horizontal plane about its center, the needle comes to rest in an approximately north-south line of direction. The same pole will always point to the north, and the other will always point toward the south. The magnetic pole that points northward is called the NORTH POLE, and the other the SOUTH POLE.

A MAGNETIC FIELD exists around a simple bar magnet. The field consists of imaginary lines along which a MAGNETIC FORCE acts. These lines emanate from the north pole of the magnet, and enter the south pole, returning to the north pole through the magnet itself, thus forming closed loops.

A MAGNETIC CIRCUIT is a complete path through which magnetic lines of force may be established under the influence of a magnetizing force. Most magnetic circuits are composed largely of magnetic materials in order to contain the magnetic flux. These circuits are similar to the ELECTRIC CIRCUIT, which is a complete path through which current is caused to flow under the influence of an electromotive force.

Magnets may be conveniently divided into three groups.

1. NATURAL MAGNETS, found in the natural state in the form of a mineral called magnetite.
2. PERMANENT MAGNETS, bars of hardened steel (or some form of alloy such as alnico) that have been permanently magnetized.

3. ELECTROMAGNETS, composed of soft-iron cores around which are wound coils of insulated wire. When an electric current flows through the coil, the core becomes magnetized. When the current ceases to flow, the core loses most of its magnetism.

Permanent magnets and electromagnets are sometimes called ARTIFICIAL MAGNETS to further distinguish them from natural magnets.

NATURAL MAGNETS

For many centuries it has been known that certain stones (magnetite, Fe_3O_4) have the ability to attract small pieces of iron. Because many of the best of these stones (natural magnets) were found near Magnesia in Asia Minor, the Greeks called the substance MAGNETITE, or MAGNETIC.

Before this, ancient Chinese observed that when similar stones were suspended freely, or floated on a light substance in a container of water, they tended to assume a nearly north-and-south position. Probably Chinese navigators used bits of magnetite floating on wood in a liquid-filled vessel as crude compasses. At that time it was not known that the earth itself acts like a magnet, and these stones were regarded with considerable superstitious awe. Because bits of this substance were used as compasses they were called LOADSTONES (or lodestones), which means "leading stones."

Natural magnets are also found in the United States, Norway, and Sweden. A natural magnet, demonstrating the attractive force at the poles, is shown in figure 1-7 (A).

ARTIFICIAL MAGNETS

Natural magnets no longer have any practical value because more powerful and more conveniently shaped permanent magnets can be produced artificially. Commercial magnets are made from special steels and alloys—for example, alnico, made principally of aluminum, nickel, and cobalt. The name is derived from the first two letters of the three principal elements of which it is composed. An artificial magnet is shown in figure 1-7 (B).

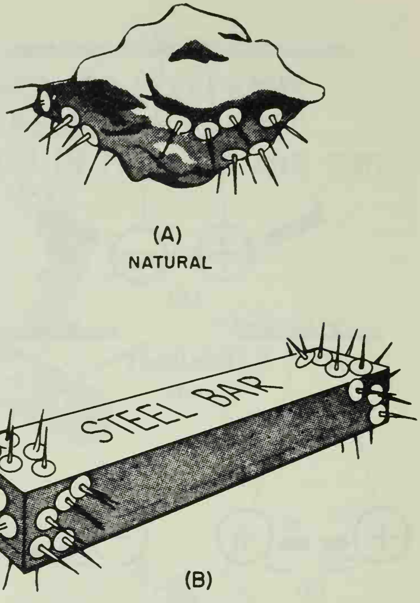
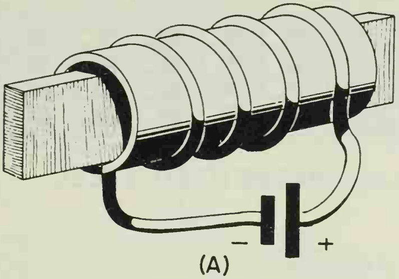


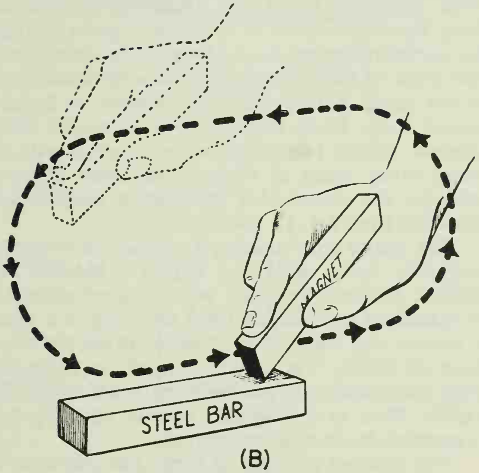
Figure 1-7.—(A) Natural magnet; (B) artificial magnet.

An iron, steel, or alloy bar can be magnetized by inserting the bar into a coil of insulated wire and passing a heavy direct current through the coil, as shown in figure 1-8 (A). This aspect of magnetism is treated later in the chapter. The same bar may also be magnetized if it is stroked with a bar magnet, as shown in figure 1-8 (B). It will then have the same magnetic property that the magnet used to induce the magnetism has—namely, there will be two poles of attraction, one at either end. This process produces a permanent magnet by INDUCTION—that is, the magnetism is induced in the bar by the influence of the stroking magnet.

Artificial magnets may be classified as "permanent" or "temporary" depending on their ability to retain their magnetic strength after the magnetizing force has been removed. Hardened steel and certain alloys are relatively difficult to magnetize and are said to have a LOW PERMEABILITY because the magnetic lines of force do not easily permeate, or distribute themselves readily through the steel. Once magnetized, however, these materials retain a large part of their magnetic strength and are called PERMANENT MAGNETS. Permanent magnets are used extensively in electric instruments, meters, telephone receivers, permanent-magnet loudspeakers, and magnetos. Conversely, substances



(A)
COIL METHOD



(B)
STROKING METHOD

Figure 1-8.—Methods of producing artificial magnets.

that are relatively easy to magnetize—such as soft iron and annealed silicon steel—are said to have a HIGH PERMEABILITY. Such substances retain only a small part of their magnetism after the magnetizing force is removed and are called TEMPORARY MAGNETS. Silicon steel and similar materials are used in transformers where the magnetism is constantly changing and in generators and motors where the strengths of the fields can be readily changed.

The magnetism that remains in a temporary magnet after the magnetizing force is removed is called RESIDUAL MAGNETISM. The fact that temporary magnets retain even a small amount of magnetism is an important factor in the buildup of voltage in self-excited d-c generators.

NATURE OF MAGNETISM

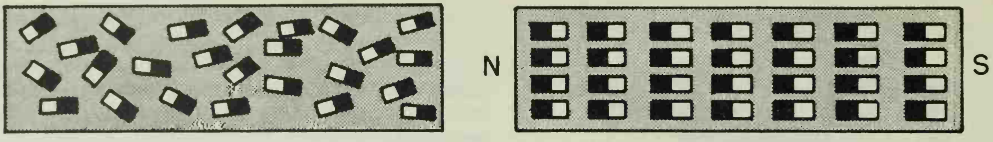
Weber's theory of the nature of magnetism is based on the assumption that each of the molecules of a magnet is itself a tiny magnet. The molecular magnets that compose an unmagnetized bar of iron or steel are arranged at random, as shown by the simplified diagram of figure 1-9 (A). With this arrangement, the magnetism of each of the molecules is neutralized by that of adjacent molecules, and no external magnetic effect is produced. When a magnetizing force is applied to an unmagnetized iron or steel bar, the molecules become alined so that the north poles point one way and the south poles point the other way, as shown in figure 1-9 (B).

If a bar magnet is broken into several parts, as in figure 1-10, each part constitutes a magnet. The north and south poles of these small magnets are in the same respective directions as those of the original magnet. If each of these parts is again broken, the resulting parts are likewise magnets, and the magnetic orientation is the same. If this breaking process could be continued, smaller and smaller pieces would retain their magnetism until each part was reduced to a molecule. It is therefore logical to assume that each of these molecules is a magnet.

A further justification for this assumption results from the fact that when a bar magnet is held out of alinement with the earth's field and is repeatedly jarred, heated, or exposed to a powerful alternating field, the molecular alinement is disarranged and the magnet becomes demagnetized. For example, electric measuring instruments become inaccurate if their permanent magnets lose some of their magnetism because of severe jarring or exposure to opposing magnetic fields.

A theory of magnetism that is perhaps more adequate than the MOLECULAR theory is the DOMAIN theory. Much simplified, this theory may be stated as follows:

In magnetic substances the "atomic" magnets, produced by the movement of the planetary electrons around the nucleus, have a strong tendency to line up together in groups of from 10^{14} to 10^{15} atoms. This occurs without the influence of any external magnetic field. These groups of atoms having their poles orientated in the same direction are called DOMAINS. Therefore, throughout each domain an intense magnetic field is produced. These



UNMAGNETIZED STEEL
(A)

MAGNETIZED STEEL
(B)

Figure 1-9.—Molecular theory of magnetism.

fields are normally in a miscellaneous arrangement so that no external field is apparent when the substance as a whole is unmagnetized. Each tiny domain (10^6 of them may be contained in 1 cubic millimeter) is always magnetized to saturation, and the addition of an external magnetic field does not increase the inherent magnetism of the individual domains.

However, if an external field that is gradually increased in strength is applied to the magnetic substance the domains will line up one by one (or perhaps several at a time) with the external field.

MAGNETIC FIELDS AND LINES OF FORCE

If a bar magnet is dipped into iron filings, many of the filings are attracted to the ends of the magnet, but none are attracted to the center of the magnet. As mentioned previously, the ends of the magnet where the attractive force is the greatest are called the POLES of the magnet. By using a compass, the line of direction of the magnetic force at various points near the magnet may be observed. The compass needle itself is a magnet. The north end of the compass needle always points toward the south pole, S, as shown in figure 1-11 (A), and thus the sense of direction (with respect to the polarity of the bar magnet) is also indicated. At the center, the compass needle points in a direction that is parallel to the bar magnet.

When the compass is placed successively at several points in the vicinity of the bar magnet the compass needle alines itself with the field at each position. The direction of the field is indicated by the arrows and represents the direction in which the north pole of the compass needle will point when the compass is placed in this field. Such a line along which a compass needle alines itself is called a MAGNETIC LINE OF FORCE. As mentioned previously, the magnetic lines of force are assumed to emanate from the north pole of a magnet, pass through the surrounding space, and enter the south pole. The lines of force then pass from the south pole to the north pole inside the magnet to form a closed loop. Each line of force forms an independent closed loop and does not merge with or cross other lines of force. The lines of force between the poles of a horseshoe magnet are shown in figure 1-11 (B).

The space surrounding a magnet, in which the magnetic force acts, is called a MAGNETIC FIELD. Michael Faraday was the first scientist to visualize the magnet field as being in a state of stress and consisting of uniformly distributed lines of force. The entire quantity of magnetic lines surrounding a magnet is called MAGNETIC FLUX. Flux in a magnetic circuit corresponds to current in an electric circuit.

The number of lines of force per unit area is called FLUX DENSITY and is measured in lines per square inch or lines per square centimeter. Flux density is expressed by the equation

$$B = \frac{\Phi}{A},$$

where B is the flux density, Φ (Greek phi) is the total number of lines of flux, and A is the cross-sectional area of the magnetic circuit. If A is in square centimeters, B is in lines per square centimeter, or GAUSS. The terms FLUX and FLOW of magnetism are frequently used in textbooks. However, magnetism itself is not thought to be a stream of particles in motion, but is simply a field of force exerted in space.

A visual representation of the magnetic field around a magnet can be obtained by placing a plate of glass over a magnet and sprinkling iron filings onto the glass. The filings arrange themselves in definite paths between the poles.

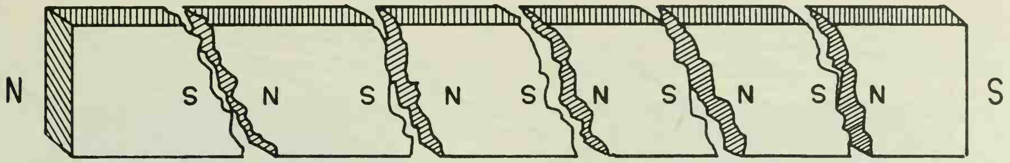
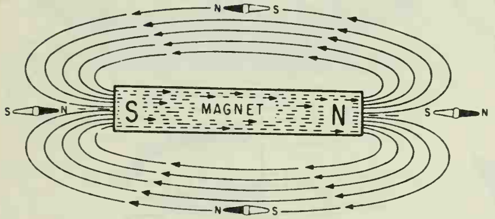
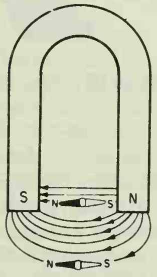


Figure 1-10.—Magnetic poles of a broken magnet.



BAR MAGNET
(A)



HORSESHOE MAGNET
(B)

Figure 1-11.—Magnetic lines of force.

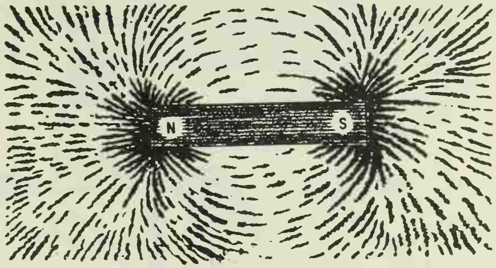


Figure 1-12.—Magnetic field pattern around a magnet.

This arrangement of the filings shows the pattern of the magnetic field around the magnet, as in figure 1-12.

The magnetic field surrounding a symmetrically shaped magnet has the following properties:

1. The field is symmetrical unless disturbed by another magnetic substance.
2. The lines of force have direction and are represented as emanating from the north pole and entering the south pole.

LAWS OF ATTRACTION AND REPULSION

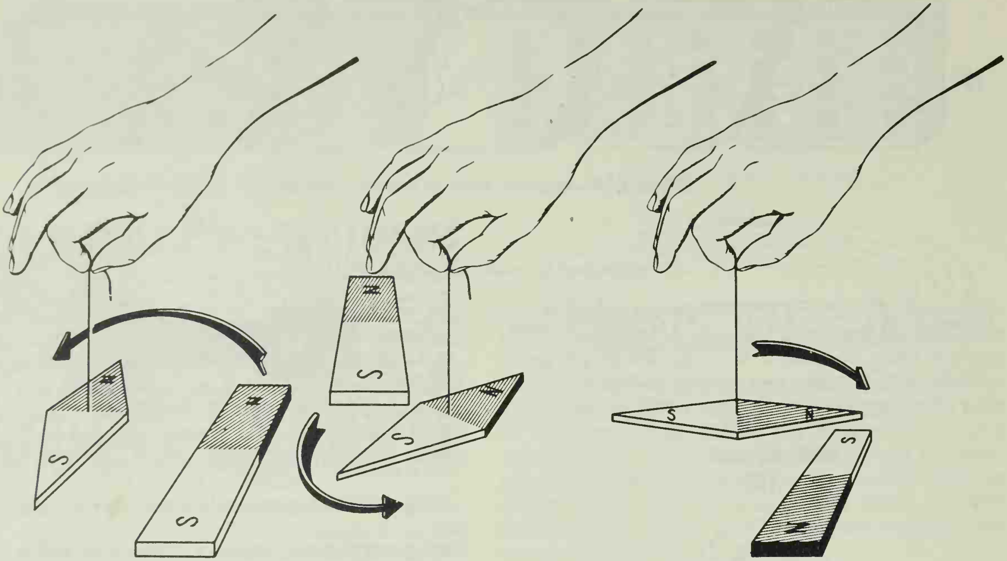
If a magnetized needle is suspended near a bar magnet, as in figure 1-13, it will be seen that a north pole repels a north pole and a south pole repels a south pole. Opposite poles, however, will attract each other. Thus, the first two laws of magnetic attraction and repulsion are:

1. LIKE magnetic poles REPEL each other.
2. UNLIKE magnetic poles ATTRACT each other.

The flux patterns between adjacent UNLIKE poles of bar magnets, as indicated by lines, are shown in figure 1-14 (A). Similar patterns for adjacent LIKE poles are shown in figure 1-14 (B). The lines do not cross at any point and they act as if they repel each other.

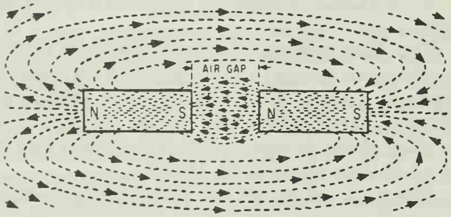
Figure 1-15 shows the flux pattern (indicated by lines) around two bar magnets placed close together and parallel with each other. Figure 1-15 (A) shows the flux pattern when opposite poles are adjacent; and figure 1-15 (B) shows the flux pattern when like poles are adjacent.

The THIRD LAW of magnetic attraction and repulsion states in effect that the force of attraction or repulsion existing between two magnetic poles decreases rapidly as the poles are separated from each other. Actually, the force of attraction or repulsion varies directly as the product of the separate pole strengths and inversely as the square of the distance separating the magnetic poles, provided the poles are small enough to be considered as points. For example, if the distance between two north poles is increased from 2 feet to 4 feet, the force of



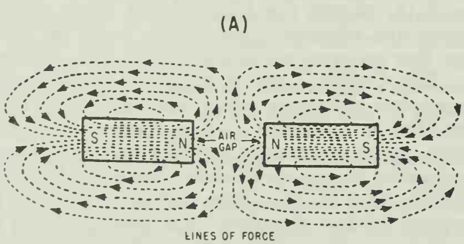
REPULSION REPULSION ATTRACTION

Figure 1-13.—Laws of attraction and repulsion.



UNLIKE POLES ATTRACT

(A)



LIKE POLES REPEL

(B)

Figure 1-14.—Lines of force between unlike and like poles.

repulsion between them is decreased to one-fourth of its original value. If either pole strength is doubled, the distance remaining the same, the force between the poles will be doubled.

THE EARTH'S MAGNETISM

As has been stated, the earth is a huge magnet; and surrounding the earth is the magnetic field produced by the earth's magnetism. The magnetic polarities of the earth are as indicated in figure 1-16. The geographic poles are also shown at each end of the axis of rotation of the earth. The magnetic axis does not coincide with the geographic axis, and therefore the magnetic and geographic poles are not at the same place on the surface of the earth.

The early users of the compass regarded the end of the compass needle that points in a northerly direction as being a north pole. The other end was regarded as a south pole. On some maps the magnetic pole of the earth towards which the north pole of the compass pointed was designated a north magnetic pole. This magnetic pole was obviously called a north pole because of its proximity to the north geographic pole.

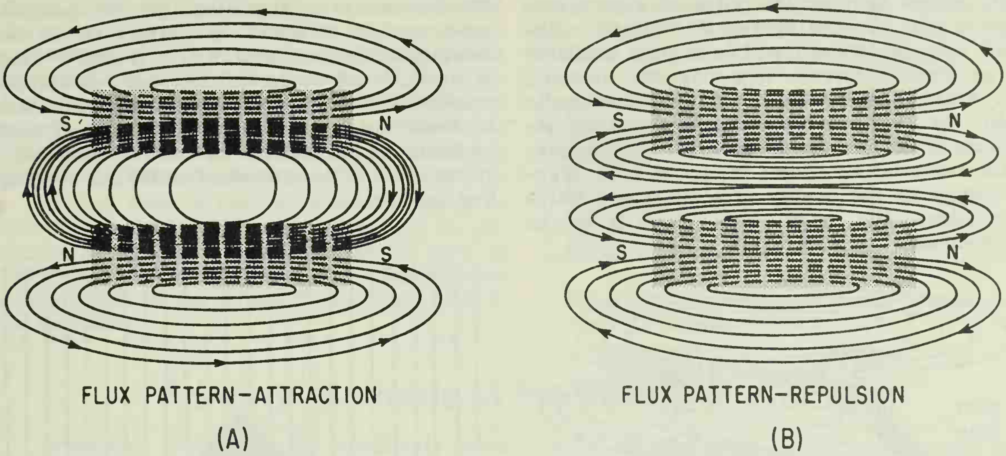


Figure 1-15.—Flux patterns of adjacent parallel bar magnets.

When it was learned that the earth is a magnet and that opposite poles attract, it was necessary to call the magnetic pole located in the northern hemisphere a SOUTH MAGNETIC POLE and the magnetic pole located in the southern hemisphere a NORTH MAGNETIC POLE. The matter of naming the poles was arbitrary. Obviously, the polarity of the compass needle that points toward the north must be opposite to the polarity of the earth's magnetic pole located there.

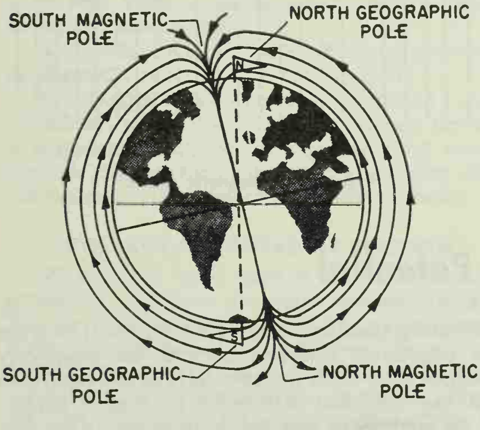


Figure 1-16.—Earth's magnetic poles.

As has been stated, magnetic lines of force are assumed to emanate from the north pole of a magnet and to enter the south pole as closed loops. Because the earth is a magnet, lines of force emanate from its north magnetic pole and enter the south magnetic pole as closed loops. The compass needle alines itself in such a way that the earth's lines of force enter at its south pole and leave at its north pole. Because the north pole of the needle is defined as the end that points in a northerly direction it follows that the magnetic pole in the vicinity of the north geographic pole is in reality a south magnetic pole, and vice versa.

Because the magnetic poles and the geographic poles do not coincide, a compass will not (except at certain positions on the earth) point in a true (geographic) north-south direction—that is, it will not point in a line of direction that passes through the north and south geographic poles, but in a line of direction that makes an angle with it. This angle is called the angle of VARIATION OR DECLINATION.

MAGNETIC SHIELDING

There is not a known INSULATOR for magnetic flux. If a nonmagnetic material is placed in a magnetic field, there is no appreciable change in flux—that is, the flux penetrates the nonmagnetic material. For example, a glass plate placed between the poles of a horseshoe magnet will have no appreciable effect on the field although glass itself is a good insulator in an electric circuit. If a magnetic material (for example, soft iron) is placed in a magnetic field, the flux may be redirected to take advantage of the greater permeability of the magnetic material as shown in figure 1-17. Permeability is the quality of a substance which determines the ease with which it can be magnetized.

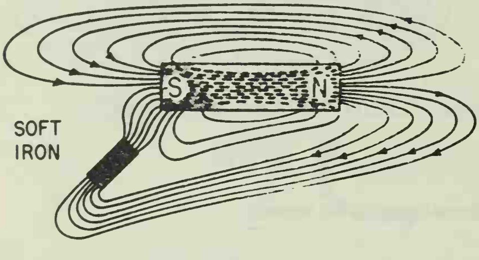


Figure 1-17.—Effects of a magnetic substance in a magnetic field.

The sensitive mechanism of electric instruments and meters can be influenced by stray magnetic fields which will cause errors in their readings. Because instrument mechanisms cannot be insulated against magnetic flux, it is necessary to employ some means of directing the flux around the instrument. This is accomplished by placing a soft-iron case, called a MAGNETIC SCREEN OR SHIELD, about the instrument. Because the flux is established more readily through the iron (even though the path is longer) than through the air inside the case, the instrument is effectively shielded, as shown by the watch and soft-iron shield in figure 1-18.

The study of electricity and magnetism, and how they affect each other, is given more thorough coverage in later chapters of this course. The discussion of magnetism up to this point has been mainly intended to clarify terms and meanings, such as "polarity," "fields," "lines of force," and so forth. Only one fundamental relationship between magnetism and electricity is discussed in this chapter. This relationship pertains to magnetism as used to generate a voltage and it is discussed under the headings that follows.

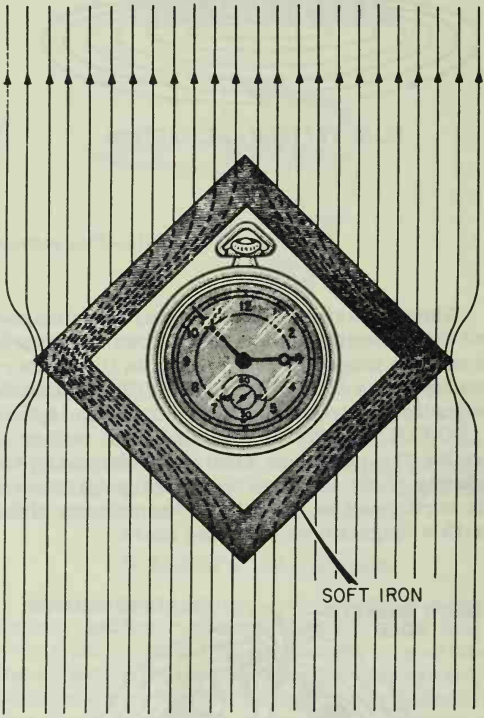


Figure 1-18.—Magnetic shield.

Difference in Potential

The force that causes free electrons to move in a conductor as an electric current is called (1) an electromotive force (e.m.f.), (2) a voltage, or (3) a difference in potential. When a difference in potential exists between two charged bodies that are connected by a conductor, electrons will flow along the conductor. This flow will be from the negatively charged body to the positively charged body until the two charges are equalized and the potential difference no longer exists.

An analogy of this action is shown in the two water tanks connected by a pipe and valve in figure 1-19. At first the valve is closed and all the water is in tank A. Thus, the water pressure across the valve is at maximum. When the valve is opened, the water flows through the pipe from A to B until the water level becomes the same in both tanks. The water then stops flowing in the pipe, because there is no longer a difference in water pressure between the two tanks.

Current flow through an electric circuit is directly proportional to the difference in potential across the circuit, just as the flow of water through the pipe in figure 1-19 is directly proportional to the difference in water level in the two tanks.

A fundamental law of current electricity is that the CURRENT IS DIRECTLY PROPORTIONAL TO THE APPLIED VOLTAGE.

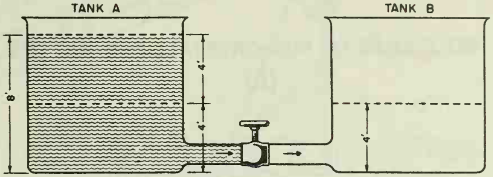


Figure 1-19.—Water analogy of electric difference in potential.

Primary Methods of Producing a Voltage

Presently, there are six commonly used methods of producing a voltage. Some of these methods are much more widely used than others. The methods of utilizing each source will be discussed, and their most common applications will be included. The following is a list of the six most common methods of producing a voltage.

1. FRICTION.—Voltage produced by rubbing two materials together.
2. PRESSURE (Piezoelectricity). — Voltage produced by squeezing crystals of certain substances.
3. HEAT (Thermoelectricity).—Voltage produced by heating the joint (junction) where two unlike metals are joined.
4. LIGHT (Photoelectricity).—Voltage produced by light striking photosensitive (light sensitive) substances.
5. CHEMICAL ACTION.—Voltage produced by chemical reaction in a battery cell.
6. MAGNETISM.—Voltage produced in a conductor when the conductor moves through a magnetic field, or a magnetic field moves through the conductor in such a manner as to cut the magnetic lines of force of the field.

VOLTAGE PRODUCED BY FRICTION

This is the least used of the six methods of producing voltages. Its main application is in Van de Graf generators, used by some laboratories to produce high voltages. As a rule, friction electricity (often referred to as static electricity) is a nuisance. For instance, a flying aircraft accumulates electric charges from the friction between its skin and the passing air. These charges often interfere with radio communication, and under some circumstances can even cause physical damage to the aircraft. You have probably received unpleasant shocks from friction electricity upon sliding across dry seat covers or walking across dry carpets, and then coming in contact with some other object.

VOLTAGE PRODUCED BY PRESSURE

This action is referred to as piezoelectricity. It is produced by compressing or decompressing crystals of certain substances. To study this form of electricity, you must first understand the meaning of the word "crystal." In a crystal, the molecules are arranged in an orderly and uniform manner. A substance in its crystallized state and in its noncrystallized state is shown in figure 1-20.

For the sake of simplicity, assume that the molecules of this particular substance are spherical (ball-shaped). In the noncrystallized state, in part (A), note that the molecules are arranged irregularly. In the crystallized state, part (B), the molecules are arranged in a regular and uniform manner. This illustrates the major physical difference between crystal and noncrystal forms of matter. Natural crystalline matter is rare; an example of matter that is crystalline in its natural form is diamond, which is crystalline carbon. Most crystals are manufactured.

Crystals of certain substances, such as Rochelle salt or quartz, exhibit peculiar electrical characteristics. These characteristics,

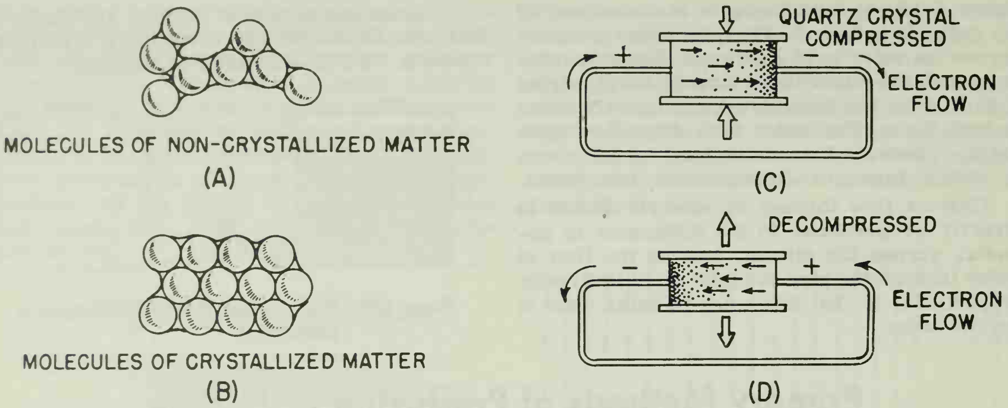

MOLECULES OF NON-CRYSTALLIZED MATTER
(A)
MOLECULES OF CRYSTALLIZED MATTER
(B)
QUARTZ CRYSTAL COMPRESSED
+
−
ELECTRON FLOW
(C)
DECOMPRESSED
−
+
ELECTRON FLOW
(D)

Figure 1-20.—(A) Noncrystallized structure, (B) crystallized structure, (C) compression of a crystal, (D) decompression of a crystal.

or effects, are referred to as ''piezoelectric.'' For instance, when a crystal of quartz is compressed, as in figure 1-20 (C), electrons tend to move through the crystal as shown. This tendency creates an electric difference of potential between the two opposite faces of the crystal. (The fundamental reasons for this action are not known. However, the action is predictable, and therefore useful.) If an external wire is connected while the pressure and e.m.f. are present, electrons will flow. If the pressure is held constant, the electron flow will continue until the charges are equalized. When the force is removed, the crystal is decompressed, and immediately causes an electric force in the opposite direction, as shown in part (D). Thus, the crystal is able to convert mechanical force, either pressure or tension, to electrical force.

The power capacity of a crystal is extremely small. However, they are useful because of their extreme sensitivity to changes of mechanical force or changes in temperature. Due to other characteristics not mentioned here, crystals are most widely used in radio communication equipment. The more complicated study of crystals, as they are used for practical applications, is left for those courses that pertain to the special ratings concerned with them.

VOLTAGE PRODUCED BY HEAT

When a length of metal, such as copper, is heated at one end, electrons tend to move away from the hot end toward the cooler end. This is true of most metals. However, in some metals, such as iron, the opposite takes place and electrons tend to move TOWARD the hot end. These characteristics are illustrated in figure 1-21. The negative charges (electrons) are moving through the copper away from the heat and through the iron toward the heat. They cross from the iron to the copper at the hot junction, and from the copper through the current meter to the iron at the cold junction. This device is generally referred to as a thermocouple.

Thermocouples have somewhat greater power capacities than crystals, but their capacity is still very small if compared to some other sources. The thermoelectric voltage in a thermocouple depends mainly on the difference in temperature between the hot and cold junctions. Consequently, they are widely used to measure temperature, and as heat-sensing devices in automatic temperature control equipment. Thermocouples generally can be subjected to much greater temperatures than ordinary thermometers, such as the mercury or alcohol types.

VOLTAGE PRODUCED BY LIGHT

When light strikes the surface of a substance, it may dislodge electrons from their orbits around the surface atoms of the substance. This occurs because light has energy, the same as any moving force.

Some substances, mostly metallic ones, are far more sensitive to light than others. That is, more electrons will be dislodged and emitted

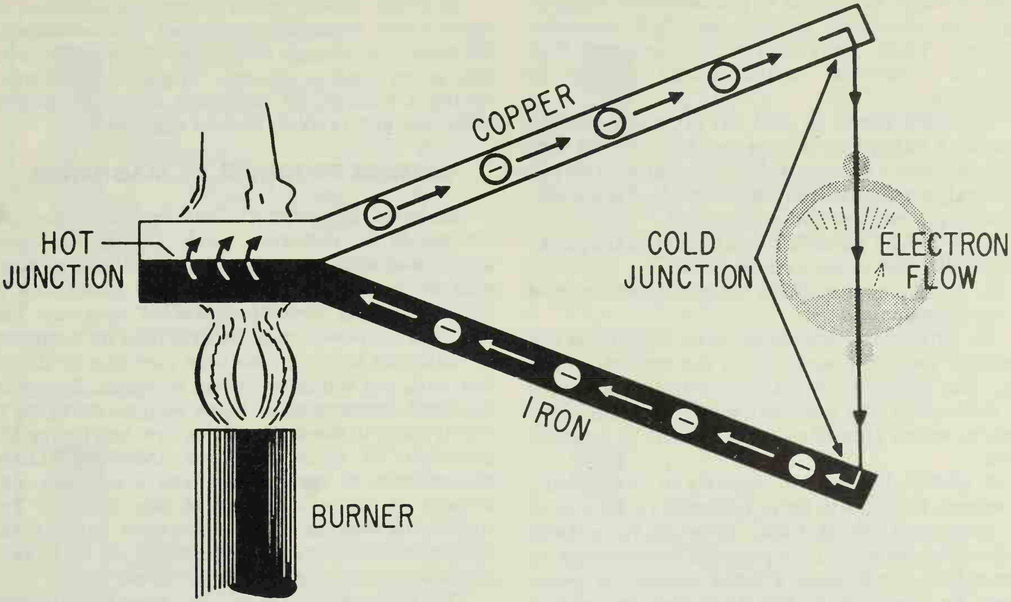

COPPER
HOT JUNCTION
COLD JUNCTION
ELECTRON FLOW
IRON
BURNER

Figure 1-21.—Voltage produced by heat.

from the surface of a highly sensitive metal, with a given amount of light, than will be emitted from a less sensitive substance. Upon losing electrons, the photosensitive (light sensitive) metal becomes positively charged, and an electric force is created. Voltage produced in this manner is referred to as "a photoelectric voltage."

The photosensitive materials most commonly used to produce a photoelectric voltage are various compounds of silver oxide or copper oxide. A complete device which operates on the photoelectric principle is referred to as a "photoelectric cell." There are many sizes and types of photoelectric cells in use, each of which serves the special purpose for which it was designed. Nearly all, however, have some of the basic features of the photoelectric cells shown in figure 1-22.

The cell shown in part (A) has a curved light-sensitive surface focused on the central anode. When light from the direction shown strikes the sensitive surface, it emits electrons toward the anode. The more intense the light, the greater is the number of electrons emitted. When a wire is connected between the filament and the back, or dark side, the accumulated electrons will flow to the dark side. These electrons will eventually

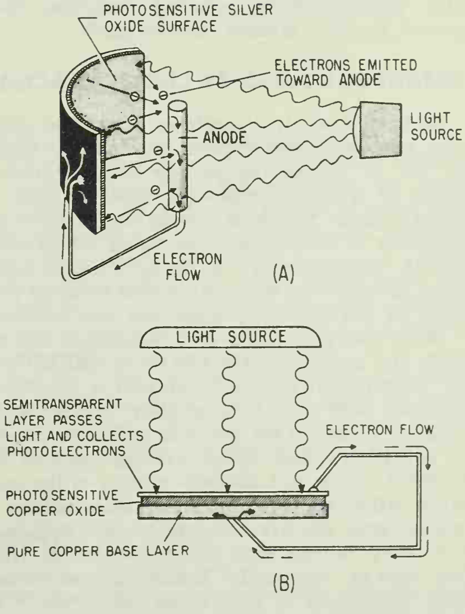

PHOTOSENSITIVE SILVER OXIDE SURFACE
ELECTRONS EMITTED TOWARD ANODE
ANODE
LIGHT SOURCE
ELECTRON FLOW
(A)
LIGHT SOURCE
SEMITRANSPARENT LAYER PASSES LIGHT AND COLLECTS PHOTOELECTRONS
ELECTRON FLOW
PHOTOSENSITIVE COPPER OXIDE
PURE COPPER BASE LAYER
(B)

Figure 1-22.—Voltage produced by light.

pass through the metal of the reflector and replace the electrons leaving the light-sensitive surface. Thus, light energy is converted to a flow of electrons, and a usable current is developed.

The cell shown in part (B) is constructed in layers. A base plate of pure copper is coated with light-sensitive copper oxide. An additional layer of metal is put over the copper oxide. This additional layer serves two purposes:

1. It is EXTREMELY thin to permit the penetration of light to the copper oxide.
2. It also accumulates the electrons emitted by the copper oxide.

An externally connected wire completes the electron path, the same as in the reflector type cell. The photocell's voltage is utilized as needed by connecting the external wires to some other device, which amplifies (enlarges) it to a usable level.

A photocell's power capacity is very small. However, it reacts to light-intensity variations in an extremely short time. This characteristic makes the photocell very useful in detecting or accurately controlling a great number of processes or operations. For instance, the photoelectric cell, or some form of the photoelectric principle, is used in television cameras, automatic manufacturing process controls, door openers, burglar alarms, and so forth.

VOLTAGE PRODUCED BY CHEMICAL ACTION

Up to this point, it has been shown that electrons may be removed from their parent atoms and set in motion by energy derived from a source of friction, pressure, heat, or light. In general, these forms of energy do not alter the molecules of the substances being acted upon. That is, molecules are not usually added, taken away, or split-up when subjected to these four forms of energy. Only electrons are involved.

When the molecules of a substance are altered, the action is referred to as CHEMICAL. For instance, if the molecules of a substance combines with atoms of another substance, or gives up atoms of its own, the action is chemical in nature. Such action always changes the chemical name and characteristics of the substance affected. For instance, when atoms of oxygen from the air come in contact with bare iron, they merge with the molecules of iron. This iron is "oxidized." It has changed chemically from iron to iron oxide, or "rust." Its molecules have been altered by chemical action.

In some cases, when atoms are added to or taken away from the molecules of a substance, the chemical change will cause the substance to take on an electric charge. The process of producing a voltage by chemical action is used in batteries and is explained in chapter 2.

VOLTAGE PRODUCED BY MAGNETISM

Magnets or magnetic devices are used for thousands of different jobs. One of the most useful and widely employed applications of magnets is in the production of vast quantities of electric power from mechanical sources. The mechanical power may be provided by a number of different sources, such as gasoline or diesel engines, and water or steam turbines. However, the final conversion of these source energies to electricity is done by generators employing the principle of electromagnetic induction. These generators, of many types and sizes, are discussed in later chapters of this course. The important subject to be discussed here is the fundamental operating principle of ALL such electromagnetic-induction generators.

To begin with, there are three fundamental conditions which must exist before a voltage can be produced by magnetism. You should learn them well, because they will be encountered again and again.
They are:

1. There must be a CONDUCTOR, in which the voltage will be produced.
2. There must be a MAGNETIC FIELD in the conductor's vicinity.
3. There must be relative motion between the field and the conductor. The conductor must be moved so as to cut across the magnetic lines of force, or the field must be moved so that the lines of force are cut by the conductor.

In accordance with these conditions, when a conductor or conductors MOVE ACROSS a magnetic field so as to cut the lines of force, electrons WITHIN THE CONDUCTOR are impelled in one direction or another. Thus, an electric force, or voltage, is created.

In figure 1-23, note the presence of the three conditions needed for creating an induced voltage:

1. A magnetic field exists between the poles of the C-shaped magnet.
2. There is a conductor (copper wire).
3. There is relative motion. The wire is moved back and forth ACROSS the magnetic field.

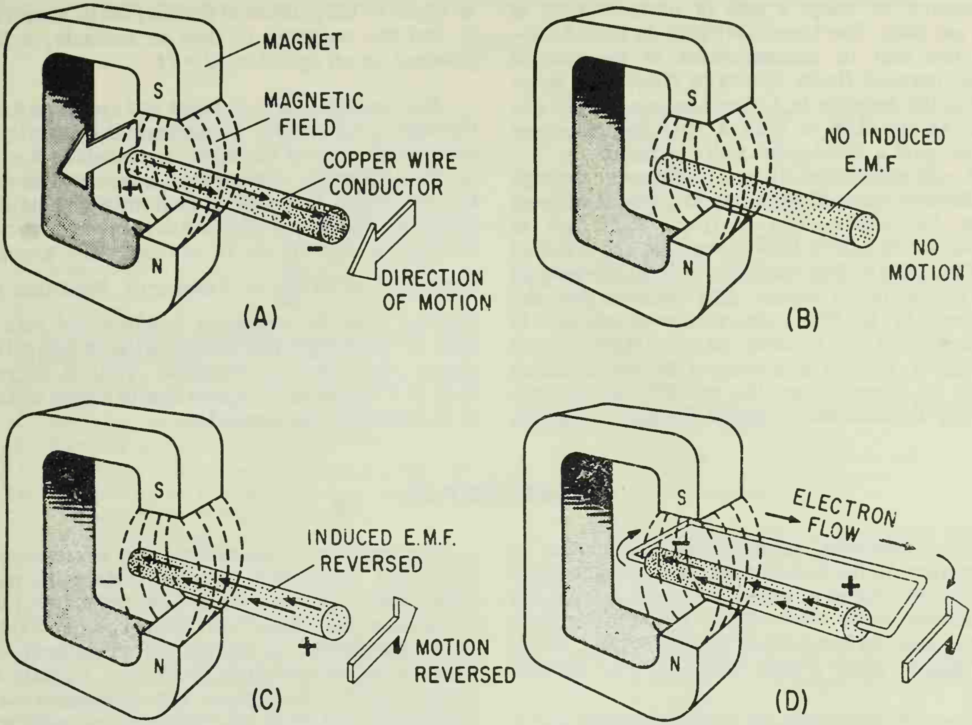


Figure 1-23.—Voltage produced by magnetism.

In part (A) the conductor is moving TOWARD you. This occurs because of the magnetically induced electromotive force (e.m.f.) acting on the electrons in the copper. The right-hand end becomes negative, and the left-hand end positive. In part (B) the conductor is stopped. This eliminates motion, one of the three required conditions, and there is no longer an induced e.m.f. Consequently, there is no longer any difference in potential between the two ends of the wire. In part (C) the conductor is moving AWAY from you. An induced e.m.f. is again created. However, note carefully that the REVERSAL OF MOTION has caused a REVERSAL OF DIRECTION in the induced e.m.f.

If a path for electron flow is provided between the ends of the conductor, electrons will leave the negative end and flow to the positive end. This condition is shown in part (D). Electron flow will continue as long as the e.m.f. exists. In studying figure 1-23, it should be noted that the induced e.m.f. could also have been created by holding the conductor stationary and moving the magnetic field back and forth.

In later chapters of this course, under the heading "Generators," you will study the more complex aspects of power generation by use of mechanical motion and magnetism.

Electric Current

The drift or flow of electrons through a conductor is called ELECTRIC CURRENT. In order to determine the amount (number) of electrons flowing in a given conductor, it is necessary to adopt a unit of measurement of current flow. The term AMPERE is used to define the unit of measurement of the rate at which current flows (electron flow). The symbol for the ampere is I. One ampere may be defined as the flow of 6.28×10^{18} electrons per second past a fixed point in a conductor.

A unit quantity of electricity is moved through an electric circuit when one ampere of current flows for one second of time. This unit is equivalent to 6.28×10^{18} electrons, and is called the COULOMB. The coulomb is to electricity as the gallon is to water. The symbol for the coulomb is Q. The rate of flow of current in amperes and the quantity of electricity moved through a circuit are related by the common factor of time. Thus, the quantity of electric charge, in coulombs, moved through a circuit is equal to the product of the current in amperes, I, and the duration of flow in seconds, t. Expressed as an equation, $Q = It$.

For example, if a current of 2 amperes flows through a circuit for 10 seconds the quantity of electricity moved through the circuit is 2 x 10, or 20 coulombs. Conversely, current flow may be expressed in terms of coulombs and time in seconds. Thus, if 20 coulombs are moved through a circuit in 10 seconds, the average current flow is $\frac{20}{10}$, or 2 amperes. Note that the current flow in amperes implies the rate of flow of coulombs per second without indicating either coulombs or seconds. Thus a current flow of 2 amperes is equivalent to a rate of flow of 2 coulombs per second.

Resistance

Every material offers some resistance, or opposition, to the flow of electric current through it. Good conductors, such as copper, silver, and aluminum, offer very little resistance. Poor conductors, or insulators, such as glass, wood, and paper, offer a high resistance to current flow.

The size and type of material of the wires in an electric circuit are chosen so as to keep the electrical resistance as low as possible. In this way, current can flow easily through the conductors, just as water flows through the pipe between the tanks in figure 1-19. If the water pressure remains constant the flow of water in the pipe will depend on how far the valve is opened. The smaller the opening, the greater the opposition to the flow, and the smaller will be the rate of flow in gallons per second.

In the electric circuit, the larger the diameter of the wires, the lower will be their electrical resistance (opposition) to the flow of current through them. In the water analogy, pipe friction opposes the flow of water between the tanks. This friction is similar to electrical resistance. The resistance of the pipe to the flow of water through it depends upon (1) the length of the pipe, (2) the diameter of the pipe, and (3) the nature of the inside walls (rough or smooth). Similarly, the electrical resistance of the conductors depends upon (1) the length of the wires, (2) the diameter of the wires, and (3) the material of the wires (copper, aluminum, etc.).

Temperature also affects the resistance of electrical conductors to some extent. In most conductors (copper, aluminum, iron, etc.) the resistance increases with temperature. Carbon is an exception. In carbon the resistance decreases as temperature increases. Certain alloys of metals (manganin and constantan) have resistance that does not change appreciably with temperature.

The relative resistance of several conductors of the same length and cross section is given in the following list with silver as a standard of 1 and the remaining metals arranged in an order of ascending resistance:

Silver	1.0
Copper	1.08
Gold	1.4
Aluminum	1.8
Platinum	7.0
Lead	13.5

The resistance in an electrical circuit is expressed by the symbol R. Manufactured circuit parts containing definite amounts of resistance are called RESISTORS. Resistance (R) is measured in OHMS. One ohm is the resistance of a circuit element, or circuit, that permits a steady current of 1 ampere (1 coulomb per second) to flow when a steady e.m.f. of 1 volt is applied to the circuit.

QUIZ

1. Soft iron is most suitable for use in a
   a. permanent magnet
   b. natural magnet
   c. temporary magnet
   d. magneto
2. Static electricity is most often produced by
   a. pressure
   b. magnetism
   c. heat
   d. friction
3. A fundamental law of electricity is that the current in a circuit is
   a. inversely proportional to the voltage
   b. equal to the voltage
   c. directly proportional to the resistance
   d. directly proportional to the voltage
4. A substance is classed as a magnet if it has
   a. the ability to conduct lines of force
   b. the property of high permeability
   c. the property of magnetism
   d. a high percentage of iron in its composition
5. If a compass is placed at the center of a bar magnet, the compass needle
   a. points to the geographic south pole
   b. points to the geographic north pole
   c. alines itself parallel to the bar
   d. alines itself perpendicular to the bar
6. When electricity is produced by heat in an iron-and-copper thermocouple,
   a. electrons move from north to south
   b. electrons move from the hot junction, through the copper, across the cold junction to the iron, and then to the hot junction
   c. electrons move from the hot junction, through the iron, across the cold junction to the copper, and then return through the copper to the hot junction
   d. none of the above is true
7. The four factors affecting the resistance of a wire are its
   a. length, material, diameter, and temperature
   b. size, length, material, and insulation
   c. length, size, relative resistance, and material
   d. size, insulation, relative resistance, and material
8. Electricity in a battery is produced by
   a. chemical action
   b. chemical reaction
   c. a chemical acting upon metallic plates
   d. all of the above
9. Resistance is always measured in
   a. coulombs
   b. henrys
   c. ohms
   d. megohms
10. The magnetic pole that points northward on a compass
    a. is called the north pole
    b. is actually a south magnetic pole
    c. points to the north magnetic pole of the earth
    d. indicates the direction of the north geographic pole
11. Of the six methods of producing a voltage, which is the least used?
    a. Chemical action
    b. Heat
    c. Friction
    d. Pressure
12. As the temperature of carbon is increased, its resistance will
    a. increase
    b. decrease
    c. remain constant
    d. double
13. Around a magnet, the external lines of force
    a. leave the magnet from the north pole and enter the south pole.
    b. often cross one another
    c. leave the magnet from the south pole and enter the north pole
    d. may be broken by a piece of iron shielding
14. When a voltage is applied to a conductor, free electrons
    a. are forced into the nucleus of their atom
    b. are impelled along the conductor
    c. unite with protons
    d. cease their movement
15. When the molecules of a substance are altered, the action is referred to as
    a. thermal
    b. photoelectric
    c. electrical
    d. chemical
16. When matter is separated into individual atoms, it
    a. has undergone a physical change only
    b. has been reduced to its basic chemicals
    c. retains its original characteristics
    d. has been reduced to its basic elements
17. Most permanent magnets and all electromagnets are
    a. classed as natural magnets
    b. manufactured in various shapes from lodestone
    c. classed as artificial magnets
    d. manufactured in various shapes from magnetite
18. When a conductor moves across a magnetic field
    a. a voltage is induced in the conductor
    b. a current is induced in the conductor
    c. both current and voltage are induced in the conductor
    d. all of the above occurs

19. The nucleus of an atom contains
    a. electrons and neutrons
    b. protons and neutrons
    c. protons and electons
    d. protons, electrons, and neutrons
20. An alnico artificial magnet is composed of
    a. magnetite, steel, and nickle
    b. cobalt, nickle, and varnish
    c. aluminum, copper, and cobalt
    d. aluminum, nickle, and cobalt
21. A material that acts as an insulator for magnetic flux is
    a. glass
    b. aluminum
    c. soft iron
    d. unknown today
22. The force acting through the distance between two dissimilarly-charged bodies
    a. is a chemical force
    b. is referred to as a magnetic field
    c. constitutes a flow of ions
    d. is referred to as an electrostatic field
23. An atom that has lost or gained electrons
    a. is negatively charged
    b. has a positive charge
    c. is said to be ionized
    d. becomes electrically neutral

24. Which of the following is considered to be the best conductor?
    a. Zinc
    b. Copper
    c. Aluminum
    d. Silver
25. As the temperature increases, the resistance of most conductors also increases.

    A conductor that is an exception to this is
    a. aluminum
    b. carbon
    c. copper
    d. brass

CHAPTER 2

BATTERIES

Storage batteries are widely used as sources of d-c voltage in automobiles, boats, aircraft, ships, telephone systems, and in portable lighting equipment. In most cases, they are used as standby power supplies. In others, batteries are the only source of power.

A battery consists of a number of CELLS assembled in a common container and connected to each other.

Common Battery Terms

THE CELL

A cell is a device that transforms chemical energy into electrical energy. The simplest cell, known as either a galvanic or voltaic cell, is shown in figure 2-1. It consists of a piece of carbon (C) and a piece of zinc (Zn) suspended in a jar that contains a solution of water (H_2O) and sulfuric acid (H_2SO_4).

The cell is the fundamental unit of the battery. A simple cell consists of two strips, or electrodes, placed in a container that also holds the electrolyte. The electrolyte in a battery may be in the form of either a liquid or a paste.

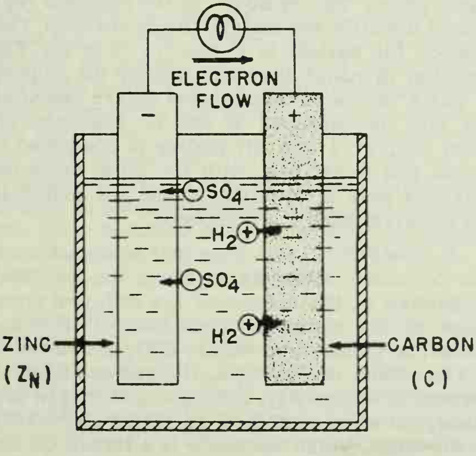

ELECTRON FLOW
−
+
SO_4^{-}
H_2^{+}
SO_4^{-}
H_2^{+}
ZINC
(ZN)
CARBON
(C)

Figure 2-1.—Simple voltaic cell.

ELECTRODES

The electrodes are the conductors by which the current leaves or returns to the electrolyte. In the simple cell, they are carbon and zinc strips that are placed in the electrolyte; while in the dry cell (fig. 2-2), they are the carbon rod in the center and the zinc container in which the cell is assembled.

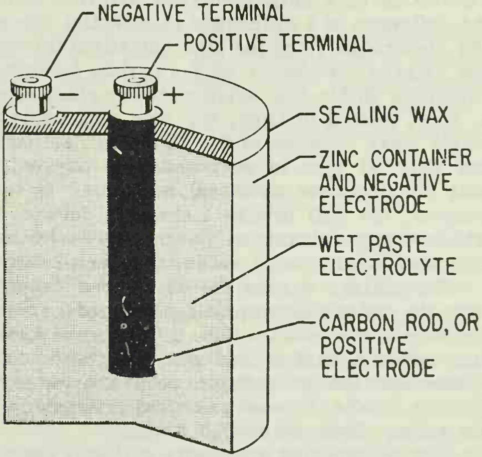

NEGATIVE TERMINAL
POSITIVE TERMINAL
−
+
SEALING WAX
ZINC CONTAINER AND NEGATIVE ELECTRODE
WET PASTE ELECTROLYTE
CARBON ROD, OR POSITIVE ELECTRODE

Figure 2-2.—Dry cell, cross-sectional view.

ELECTROLYTE

The electrolyte is the solution that acts upon the electrodes which are placed in it. The electrolyte may be a salt, an acid, or an alkaline solution. In the simple galvanic cell and in the automobile storage battery, the electrolyte is in a liquid form; while in the dry cell, the electrolyte is a paste.

PRIMARY CELL

A primary cell is one in which the chemical action eats away one of the electrodes, usually the negative. When this happens, the electrode must be replaced or the cell must be thrown away. In the galvanic type cell the zinc electrode and the liquid solution are usually replaced when this happens. In the case of the dry cell, it is usually cheaper to buy a new cell. The simple voltaic cell is a primary cell.

SECONDARY CELL

A secondary cell is one in which the electrodes and the electrolyte are altered by the chemical action that takes place when the cell delivers current. These cells may be restored to their original condition by forcing an electric current through them in the opposite direction to that of discharge. The automobile storage battery is a common example of the secondary cell.

THE BATTERY

The battery consists of two or more cells placed in a common box or container. The cells are connected to each other in series, in parallel, or in some combination of series and parallel, depending upon the amount of voltage and current required of the battery. For example, a 45-volt B battery used for radio work may consist of 30 cells of 1-1/2 volts each, connected in series. The 12-volt battery used in the automobile of today consists of 6 cells of 2 volts each, connected in series.

Battery Chemistry

ACTION ON DISCHARGE

If a conductor is connected externally to the electrodes of a cell, electrons will flow under the influence of a difference in potential across the electrodes from the zinc (negative) through the external conductor to the carbon (positive) returning within the solution to the zinc. After a short period of time, the zinc will begin to waste away because of the ''burning'' action of the acid. If zinc is surrounded by oxygen, it will burn(become oxidized) as a fuel. In this respect, the cell is like a chemical furnace in which energy released by the zinc is transformed into electrical energy rather than heat energy.

The voltage across the electrodes depends upon the materials comprising them and the composition of the solution. The difference of potential between carbon and zinc electrodes in a dilute solution of sulfuric acid and water is about 1.5 volts. In most practical primary cells the voltage does not exceed 2 volts.

The current that a primary cell may deliver depends upon the resistance of the entire curcuit, including that of the cell itself. The internal resistance of the primary cell depends upon the size of the electrodes, the distance between them in the solution, and the resistance of the solution. The larger the electrodes and the closer together they are in solution (without touching), the lower will be the internal resistance of the primary cell and the more current it will be capable of supplying to a load.

When current flows through a cell, the zinc will gradually be dissolved in solution and the acid will be neutralized. A chemical equation is sometimes used to show the chemical action that takes place. The symbols in the equation represent the different materials that are used. The symbol for carbon is C and for zinc Zn. The equation is quantitative and equates the number of parts of the materials used before and after the zinc is oxidized. It will be remembered from chapter 1 that all matter is composed of atoms and molecules, with the atom being the smallest part of an element and the molecule the smallest part of a compound.

A COMPOUND is a chemical combination of two or more elements in which the physical properties of the compound are different from those of the elements comprising it. For instance, a molecule of water, H_2O, is composed of two atoms of hydrogen, H_2, and one atom of oxygen, O. Ordinarily, hydrogen and oxygen are gases, but when combined, as stated above, they form water, which normally is a liquid. On the other hand, sulfuric acid, H_2SO_4, and water,

H_2O form a MIXTURE (not a compound), because the identity of both liquids is preserved when they are in solution together.

When a current flows through a primary cell having carbon and zinc electrodes and a dilute solution of sulfuric acid and water, the chemical reaction that takes place can be expressed as:

$$Zn + H_2SO_4 + H_2O \xrightarrow[\text{discharge}]{} ZnSO_4 + H_2O + H_2\uparrow.$$

The expression indicates that as current flows, a molecule of zinc combines with a molecule of sulfuric acid to form a molecule of zinc sulfate ($ZnSO_4$) and a molecule of hydrogen (H_2). The zinc sulfate dissolves in solution and the hydrogen appears as gas bubbles around the carbon electrode. As current continues to flow, the zinc is gradually consumed and the solution changes to zinc sulfate and water. The carbon electrode does not enter into the chemical changes taking place but simply provides a return path for the current.

In the process of oxidizing the zinc, the solution breaks up into positive and negative ions that move in opposite directions through the solution (fig. 2-1). The positive ions are hydrogen ions that appear around the carbon electrode (positive terminal). They are attracted to it by the free electrons from the zinc that are returning to the cell by way of the external load and the positive carbon terminal. The negative ions are SO_4 ions that appear around the zinc electrode. Positive zinc ions enter the solution around the zinc electrode and combine with the negative SO_4 ions to form zinc sulfate, $ZnSO_4$, a grayish-white substance that dissolves in water. At the same time that the positive and negative ions are moving in opposite directions in the solution, electrons are moving through the external circuit from the negative zinc terminal, through the load, and back to the positive carbon terminal. When the zinc is used up, the voltage of the cell is reduced to zero. There is no appreciable difference in potential between zinc sulfate and carbon in a solution of zinc sulfate and water.

POLARIZATION

The chemical action that takes place in the cell (fig. 2-1) while the current is flowing causes hydrogen bubbles to form on the surface of the positive carbon electrode in great numbers until the entire surface is surrounded. This action is called POLARIZATION. Some of these bubbles rise to the surface of the solution and escape into the air. However, many of the bubbles remain until there is no room for any more to be formed.

The hydrogen tends to set up an electromotive force in the opposite direction to that of the cell, thus increasing the effective internal resistance, reducing the output current, and lowering the terminal voltage.

A cell that is heavily polarized has no useful output. There are several ways to prevent polarization from occurring or to overcome it after it has occurred. The very simplest method might be to remove the carbon electrode and wipe off the hydrogen bubbles. When the electrode is replaced in the electrolyte, the e.m.f. and current are again normal. This method is not practicable because polarization occurs rapidly and continuously in the simple voltaic cell. A commercial form of voltaic cell, known as the DRY CELL, employs a substance rich in oxygen as a part of the positive carbon electrode, which will combine chemically with the hydrogen to form water, H_2O. One of the best depolarizing agents used is manganese dioxide (MnO_2), which supplies enough free oxygen to combine with all of the hydrogen so that the cell is practically free from polarization.

The chemical action that occurs may be expressed as

$$2MnO_2 + H_2 \rightarrow Mn_2O_3 + H_2O.$$

The manganese dioxide combines with the hydrogen to form water and a lower oxide of manganese. Thus the counter e.m.f. of polarization does not exist in the cell, and the terminal voltage and output current are maintained normal.

LOCAL ACTION

When the external circuit is opened, the current will cease to flow, and theoretically all chemical action within the cell will stop. However, commercial zinc contains many impurities, such as iron, carbon, lead, and arsenic. These impurities form many small cells within the zinc electrode in which current flows between the zinc and its impurities. Thus the zinc is oxidized even though the cell itself is an open circuit. This wasting away of the zinc on open circuit is called LOCAL ACTION. For example, a small local cell exists on a zinc plate containing impurities of iron, as shown in figure 2-3. Electrons flow between the zinc and iron and the solution around the impurity becomes ionized. The negative SO_4 ions combine with the positive

Zn ions to form $ZnSO_4$. Thus the acid is depleted in solution and the zinc consumed.

Local action may be prevented by using pure zinc (which is not practical), by coating the zinc with mercury, or by adding a small percentage of mercury to the zinc during the manufacturing process. The treatment of the zinc with mercury is called AMALGAMATING the zinc. Since mercury is 13.6 times as heavy as an equal volume of water, small particles of impurities having a lower relative weight than that of mercury will rise (float) to the surface of the mercury. The removal of these impurities from the zinc prevents local action. The mercury is not readily acted upon by the acid, and even when the cell is delivering current to a load, the mercury continues to act on the impurities in the zinc, causing them to leave the surface of the zinc electrode and float to the surface of the mercury. This process greatly increases the life of the primary cell.

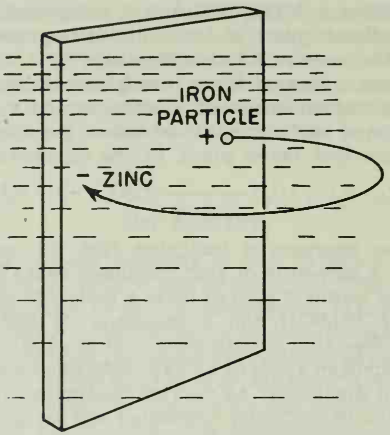


Figure 2-3.—Local action on zinc electrode.

Types of Batteries

THE DRY (PRIMARY) CELL

The dry cell is so called because its electrolyte is not in a liquid state. Actually, the electrolyte is a moist paste. If it should become dry, it would no longer be able to transform chemical energy to electrical energy. The name DRY CELL, therefore, is not strictly correct in a technical sense.

Construction of the Dry Cell

The construction of a common type of dry cell is shown in figure 2-4. The internal parts of the cell are located in a cylindrical zinc container. This zinc container serves as the cell's negative electrode. The container is lined with a nonconducting material, such as blotting paper, to insulate the zinc from the paste. A carbon electrode is located in the center, and it serves as the positive terminal of the cell. The paste is a mixture of several substances. Its composition may vary, depending on its manufacturer. Generally, however, the paste will contain some combination of the following substances: ammonium chloride (sal ammoniac), powdered coke, ground carbon, manganese dioxide, zinc chloride, graphite, and water.

This paste, which is packed in the space between the carbon and the blotting paper, also serves to hold the carbon electrode rigid in the center of the cell. When packing the paste in the cell, a small expansion space is left at the top. The cell is then sealed with asphalt-saturated cardboard.

Binding posts are attached to the electrodes so that wires may be conveniently connected to the cell.

Since the zinc container is one of the electrodes, it must be protected with some insulating material. Therefore, it is common practice for the manufacturer to enclose the cells in cardboard containers.

Chemical Action of the Dry Cell

The dry cell (fig. 2-4) is fundamentally the same as the simple voltaic cell (wet cell) described earlier, as far as its internal chemical action is concerned. The action of the water and the ammonium chloride in the paste, together with the zinc and carbon electrodes, produces the voltage of the cell. The manganese dioxide is added to reduce the polarization when line current flows, and the zinc chloride reduces local action when the cell is idle. The blotting paper serves two purposes, one being to keep the paste from making actual contact with the zinc container and the other being to permit the electrolyte to filter through to the zinc slowly. The cell is sealed at the top to keep air from entering and drying the electrolyte. Care should be taken to prevent breaking this seal.

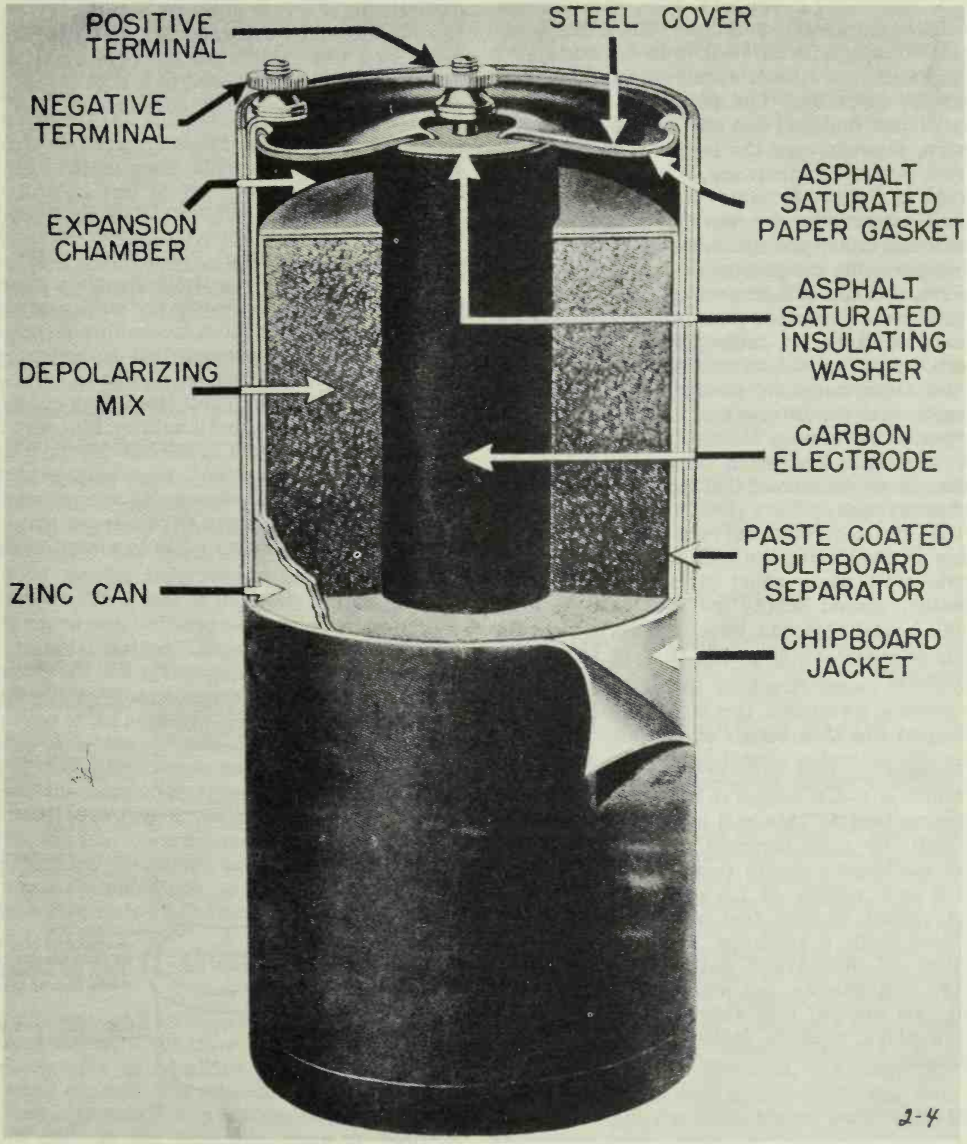

POSITIVE TERMINAL
STEEL COVER
NEGATIVE TERMINAL
ASPHALT SATURATED PAPER GASKET
EXPANSION CHAMBER
ASPHALT SATURATED INSULATING WASHER
DEPOLARIZING MIX
CARBON ELECTRODE
PASTE COATED PULPBOARD SEPARATOR
ZINC CAN
CHIPBOARD JACKET
2-4

Figure 2-4.—Cutaway view of the general-purpose dry cell.

Rating of the Standard Size Cell

One of the most popular sizes in general use is the standard, or No. 6, dry cell. It is approximately 2-1/2 inches in diameter and 6 inches in length. The voltage is about 1-1/2 volts when new but decreases as the cell ages. When the open-circuit voltage falls below 0.75 to 1.2 volts (depending upon the circuit requirements), the cell is usually discarded. The amount of current that the cell can deliver, and still give satisfactory service, depends upon the length of time that the current flows. For instance, if a No. 6 cell is to be used in a portable radio, it is likely to supply current constantly for several hours. Under these conditions, the current should not exceed 1/8 ampere, the rated constant-current capacity of a No. 6 cell. If the same cell is required to supply current only occasionally, for only short periods of time, it could supply currents of several amperes without undue injury to the cell. As the time duration of each discharge decreases, and the interval of time between discharges increases the allowable amount of current available for each discharge becomes higher, up to the amount that the cell will deliver on short circuit.

The short-circuit current test is another means of evaluating the condition of a dry cell. A new cell, when short circuited through an ammeter, should supply not less than 25 amperes. A cell that has been in service should supply at least 10 amperes if it is to remain in service.

Rating of the Unit Size Cell

Another popular size of dry cell is the size D, which is 1-3/8 inches in diameter and 2-3/4 inches in length. This cell is also known as the unit cell. Its most common use is in standard-sized flashlights and in test instruments. The size D cell voltage is 1.5 volts when new. The short-circuit current test of a new cell should be from 5 to 6 amperes. The corrosion and swelling of discharged cells may ruin flashlights, instruments, or whatever device uses them. To prevent this action, some manufacturers place a steel jacket around the zinc container.

Shelf Life

A cell that is not put into use (sits on the shelf) will gradually deteriorate because of slow internal chemical actions (local action) and changes in moisture content. However, this deterioration is usually very slow if cells are properly stored. High-grade cells of the larger sizes, such as the standard No. 6, should have a shelf life of a year or more. Smaller size cells have a proportionately shorter shelf life, ranging down to a few months for the very small sizes. If unused cells are stored in a cool place, their shelf life will be greatly increased.

Mercury Cells

A fairly recent addition to the types of batteries used in the Navy is the mercury cell. It is known also as the ''Ruben'' or ''RM'' cell. Presently, its uses are limited mainly to precision measuring instruments and guided missiles. The mercury cell's most desirable characteristics are (1) a high power-output-to-weight ratio, (2) an almost flat discharge-voltage curve, and (3) a relatively long shelf life under conditions of high temperature and humidity. Mercury cells presently in use, such as the RM-1R and RM-4R, are very small compared to most lead-acid cells. However, larger mercury cells are presently in the developmental stage. The approximate size of two typical mercury cells is shown in figure 2-5 (A).

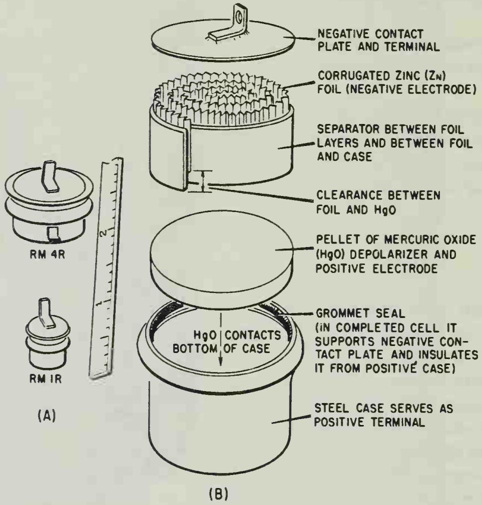

NEGATIVE CONTACT PLATE AND TERMINAL
CORRUGATED ZINC (Zn) FOIL (NEGATIVE ELECTRODE)
SEPARATOR BETWEEN FOIL LAYERS AND BETWEEN FOIL AND CASE
CLEARANCE BETWEEN FOIL AND HgO
PELLET OF MERCURIC OXIDE (HgO) DEPOLARIZER AND POSITIVE ELECTRODE
GROMMET SEAL (IN COMPLETED CELL IT SUPPORTS NEGATIVE CONTACT PLATE AND INSULATES IT FROM POSITIVE CASE)
STEEL CASE SERVES AS POSITIVE TERMINAL
HgO BOTTOM
CONTACTS OF CASE
RM 4R
RM 1R
(A)
(B)

Figure 2-5.—Size and construction of typical mercury (RM) cells.

Mercury cells, as compared to lead-acid cells, are also quite different in their internal construction, as shown by the exploded view in figure 2-5 (B). The negative electrode is corrugated zinc foil, spirally co-wrapped with an inert separator. The zinc is coated with pure mercury (amalgamated) to prevent local action during shelf storage. In the completed cell, the top contact plate connects to the spiralled edge of the zinc foil. The bottom of the separator rests against the mercuric oxide pellet; and the pellet is, in turn, pressed tightly against the bottom of the steel case. There is space in the foil corrugations and in the clearance between the foil and HgO pellet. This space is filled with electrolyte. The electrolyte is an alkaline solution of potassium hydroxide, zincate, and water. The cell is sealed, since there is no gassing during discharge. Mercury cells cannot be recharged.

The overall chemical action by which the mercury cell produces electricity is given by the following chemical formula:

$$Zn + H_2O + HgO \longrightarrow ZnO + H_2O + Hg.$$

This action, the same as in other type cells, is a process of oxidation. The alkaline electrolyte is in contact with the zinc electrode. The zinc oxidizes (Zn changes to ZnO), thus taking atoms of oxygen from water molecules in the electrolyte. This leaves positive hydrogen ions, which move toward the mercuric oxide pellet, causing polarization. These hydrogen ions take oxygen from the mercuric oxide (thus changing HgO to Hg). Where one molecule of water is destroyed at the negative electrode, one molecule is produced at the positive electrode, maintaining the net amount of water constant. By absorbing oxygen, the zinc electrode accumulates excess electrons, making it negative. By giving up oxygen, the mercuric oxide electrode loses electrons, making it positive. In the discharged state, the negative electrode is zinc oxide, and the positive electrode is ordinary mercury.

Reserve Cell

A reserve cell is one in which the elements are kept dry until the time of use at which time the electrolyte is admitted and the cell starts producing current. The rigorous requirements of the proximity fuse led to the development of this type of cell. In the proximity fuse the battery consists of 63 annular (or ring-shaped) zinc and carbon electrodes. A glass container is mounted in the center of the electrodes. The shock of the acceleration produced by firing the shell breaks the glass container and forces the electrolyte between the electrodes, thus activating the cell.

The shelf life of primary reserve batteries is extremely long even under adverse tropic or arctic conditions. This life is attained by incorporating the depolarizer in the liquid electrolyte so that the elements of the cell are subject to no chemical action until the time of use.

Combining Cells

In many cases, a battery-powered device may require more electrical energy than one cell can provide. The device may require either a higher voltage or more current, and in some cases both. Under such conditions it is necessary to combine, or interconnect, enough cells to meet the higher requirements. Cells connected in series provide a higher voltage, while cells connected in parallel provide a higher current capacity. To provide adequate power when both voltage and current requirements are greater than one cell's capacity, a combination series-parallel network of cells must be interconnected.

SERIES-CONNECTED CELLS

Assume you must connect enough No. 6 dry cells to supply power to a load requiring 6 volts. At this potential, the load will draw 1/8 ampere. Since a single No. 6 cell supplies a potential of only 1.5 volts, more than one cell is obviously needed. To obtain the higher potential, the cells are connected in series as shown in figure 2-6 (A).

In a series hookup, the negative electrode of the first cell is connected to the positive electrode of the second cell, the negative electrode of the second to the positive of the third, and so on. The positive electrode of the first cell and negative electrode of the last cell then serve as the power takeoff terminals of the battery. In this way, the potential is boosted 1.5 volts by each cell in the series line. There are four cells, so the output terminal voltage is 1.5 x 4 = 6 volts. When connected to the load, 1/8 ampere flows through the load and each cell of the battery. This is within the capacity of each No. 6 cell. Therefore, only four series-connected No. 6 cells are needed to supply this particular load.

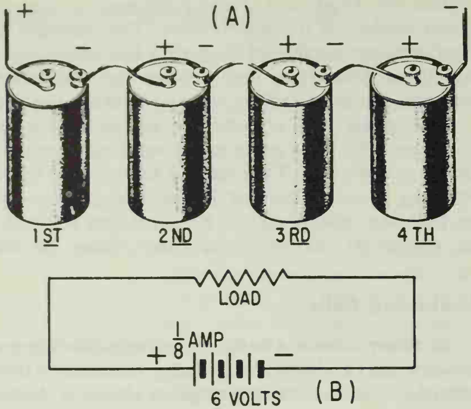


Figure 2-6.—(A) Pictorial view of series-connected cells; (B) schematic of series connection.

PARALLEL-CONNECTED CELLS

In this case, assume an electrical load requires only 1.5 volts, but will draw 1/2 ampere of current. (Assume that a No. 6 cell will supply only 1/8 ampere.) To meet this requirement, the No. 6 cells are connected in parallel, as shown in figure 2-7 (A). In a parallel connection, all positive cell electrodes are connected to one line, and all negative electrodes are connected to the other. No more than one cell is connected between the lines at any one point, so the potential between the lines is the same as that of one cell, or 1.5 volts. However, each cell may contribute its maximum allowable current of 1/8 ampere to the line. There are four cells, so the total line current is 1/8 x 4 = 1/2 ampere. Hence, four No. 6 cells in parallel have enough capacity to supply a load requiring 1/2 ampere at 1.5 volts.

SERIES-PARALLEL CONNECTED CELLS

Figure 2-8 depicts a battery network supplying power to a load requiring both a voltage and current greater than one cell can provide. To provide the required 4-1/2 volts, groups of three 1.5-volt cells are connected in series. To provide the required 1/2 ampere of current, four series groups are connected in parallel, each supplying 1/8 ampere of current.

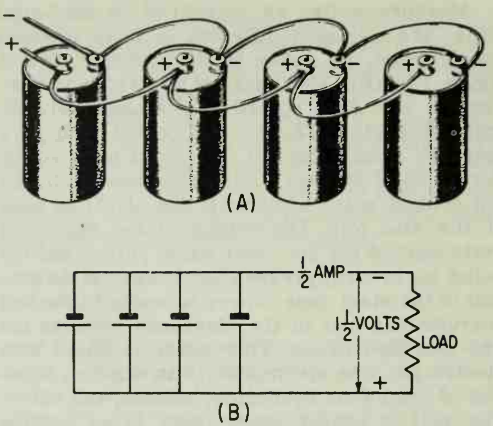


Figure 2-7.—(A) Pictorial view of parallel-connected cells; (B) schematic of parallel connections.

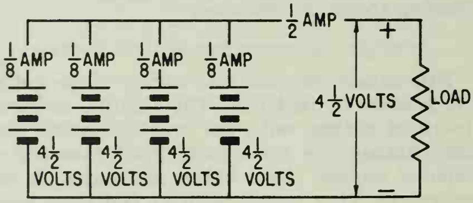


Figure 2-8.—Series-parallel connected cells.

SECONDARY (WET) CELLS

Secondary cells function on the same basic chemical principles as primary cells. They differ mainly in that they may be recharged, whereas the primary cell is not rechargeable. Some of the materials of a primary cell are consumed in the process of changing chemical energy to electrical energy. In the secondary cell, the materials are merely transferred from one electrode to the other as the cell discharges. Discharged secondary cells may be restored (charged) to their original state by forcing an electric current from some other source through the cell in the opposite direction to that of discharge.

The storage battery consists of a number of secondary cells connected in series. Properly speaking, this battery does not store electrical energy, but is a source of chemical energy which produces electrical energy. There are three types of storage cells--the lead-acid type, which has an e.m.f. of 2.2 volts per cell; the nickel-iron-alkali type; and the nickel-cadmium-alkaline type. The latter two have an e.m.f. of 1.2 volts per cell. Of these three types, the lead-acid type is the most widely used, and will be described first.

Lead-Acid Batteries

In its charged condition, the active materials in the lead-acid battery are lead peroxide (used as the positive plate) and sponge lead (used as the negative plate). The electrolyte is a mixture of sulfuric acid and water. The strength (acidity) of the electrolyte is measured in terms of its specific gravity. Specific gravity is the ratio of the weight of a given volume of electrolyte to an equal volume of pure water. Concentrated sulfuric acid has a specific gravity of about 1.830; pure water has a specific gravity of 1.000. The acid and water are mixed in a proportion to give the specific gravity desired. For example, an electrolyte with a specific gravity of 1.210 requires roughly one part of concentrated acid to four parts of water.

In a fully charged battery the positive plates are pure lead peroxide and the negative plates are pure lead. Also, in a fully charged battery, all the acid is in the electrolyte so that the specific gravity is at its maximum value. The active materials of both the positive and negative plates are porous, and have absorptive qualities similar to a sponge.

The pores are therefore filled with the battery solution (electrolyte) in which they are immersed. As the battery discharges, the acid in contact with the plates separates from the electrolyte. It forms a chemical combination with the plate's active material, changing it to lead sulfate. Thus, as the discharge continues, lead sulfate forms on the plates, and more acid is taken from the electrolyte. The electrolyte's water content becomes progressively higher; that is, the ratio of water to acid increases. As a result, the specific gravity of the electrolyte will gradually decrease during discharge.

When the battery is being charged, the reverse takes place. The acid held in the sulfated plate material is driven back into the electrolyte; further charging cannot raise its specific gravity any higher. When fully charged, the material of the positive plates is again pure lead peroxide and that of the negative plates is pure lead.

Electrical energy is derived from a cell when the plates react with the electrolyte. As a molecule of sulfuric acid separates, part of it combines with the negative sponge lead plates. Thus, it makes the sponge lead plates negative, and at the same time forms lead sulfate. The remainder of the sulfuric acid molecule, lacking electrons, has thus become a positive ion. The positive ions migrate through the electrolyte to the opposite (lead peroxide) plates, and takes electrons from them. This action neutralizes the positive ions, forming ordinary water. It also makes the lead peroxide plates positive, by taking electrons from them. Again, lead sulfate is formed in the process.

The action just described is represented in more detail by the following chemical equation

$$Pb + PbO_2 + 2H_2SO_4 \overset{\text{discharging}}{\rightleftharpoons} 2PbSO_4 + 2H_2O.$$

The left side of the expression represents the cell in the charged condition, and the right side represents the cell in the discharged condition.

In the charged condition the positive plate contains lead peroxide, PbO_2; the negative plate is composed of sponge lead, Pb; and the solution contains sulfuric acid, H_2SO_4. In the discharged condition both plates contain lead sulfate, $PbSO_4$, and the solution contains water, H_2O. As the discharge progresses, the acid content of the electrolyte becomes less and less because it is used in forming lead sulfate, and the specific gravity of the electrolyte decreases. A point is reached where so much of the active material has been converted into lead sulfate that the cell can no longer produce sufficient current to be of practical value. At this point the cell is said to be discharged (fig. 2-9 (C)). Since the amount of sulfuric acid combining with the plates at any time during discharge is in direct proportion to the ampere-hours (product of current in amperes and time in hours) of discharge, the specific gravity of the electrolyte is a guide in determining the state of discharge of the lead-acid cell.

If the discharged cell is properly connected to a direct-current charging source the voltage of which is slightly higher than that of the cell, current will flow through the cell, in the opposite direction to that of discharge, and the cell is said to be charging (fig. 2-9 (D)). The effect of the current will be to change the lead sulfate on both the positive and negative plates back to its original active form of lead peroxide and sponge lead, respectively. At the same time, the sulfate is restored to the electrolyte with the result that the specific gravity of the electrolyte increases. When all the sulfate has been restored to the electrolyte, the specific gravity will be maximum. The cell is then fully charged and is ready to be discharged again.

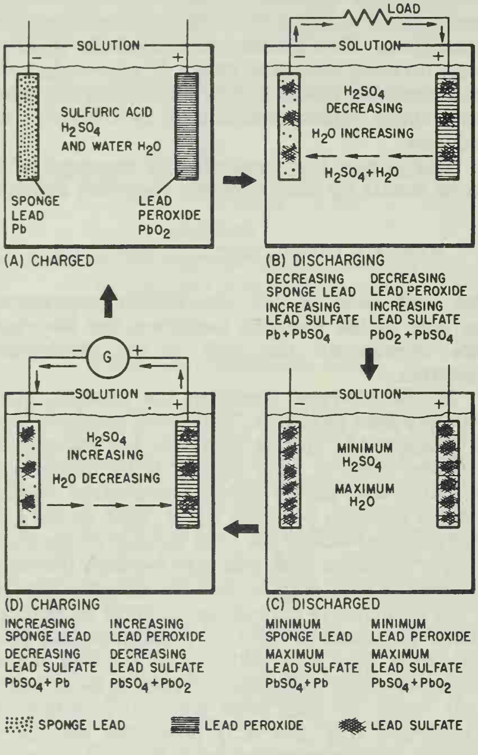

SOLUTION
−
+
SULFURIC ACID
H_2SO_4
AND WATER H_2O
SPONGE LEAD Pb
LEAD PEROXIDE PbO_2
(A) CHARGED
LOAD
SOLUTION
H_2SO_4 DECREASING
H_2O INCREASING
$H_2SO_4+H_2O$
(B) DISCHARGING
DECREASING SPONGE LEAD
DECREASING LEAD PEROXIDE
INCREASING LEAD SULFATE
INCREASING LEAD SULFATE
$Pb+PbSO_4$
PbO_2+PbSO_4
G
SOLUTION
H_2SO_4 INCREASING
H_2O DECREASING
(D) CHARGING
INCREASING SPONGE LEAD
INCREASING LEAD PEROXIDE
DECREASING LEAD SULFATE
DECREASING LEAD SULFATE
$PbSO_4+Pb$
$PbSO_4+PbO_2$
SOLUTION
MINIMUM H_2SO_4
MAXIMUM H_2O
(C) DISCHARGED
MINIMUM SPONGE LEAD
MINIMUM LEAD PEROXIDE
MAXIMUM LEAD SULFATE
MAXIMUM LEAD SULFATE
$PbSO_4+Pb$
$PbSO_4+PbO_2$
SPONGE LEAD
LEAD PEROXIDE
LEAD SULFATE

Figure 2-9.—Chemical action in lead-acid cell.

It should always be remembered that the addition of sulfuric acid to a discharged lead-acid cell does not recharge the cell. Adding acid only increases the specific gravity of the electrolyte and does not convert the lead sulfate on the plates back into active material (sponge lead and lead peroxide), and consequently does not bring the cell back to a charged condition. A charging current must be passed through the cell to do this.

As a cell charge nears completion, hydrogen gas, H_2, is liberated at the negative plate and oxygen gas, O_2, is liberated at the positive plate. This action occurs because the charging current is greater than the amount that is necessary to reduce the small remaining amount of lead sulfate on the plates. Thus, the excess current ionizes the water in the electrolyte. This action is necessary to assure full charge to the cell.

PASTED PLATES

Lead-acid storage batteries use a variety of plates ranging from the spun-lead (Plante) type to the lighter pasted construction. The Plante-type plates require repeated charging and discharging to develop the active material to the proper depth. The process is slow and expensive. In 1881 Camille Faure in France made a radical improvement in the construction of storage batteries by developing a pasted plate that was manufactured with much less expense.

The pasted plate is most commonly used in portable lead-acid batteries today. The plates are formed by applying special lead-oxide pastes to a grid made of lead-antimony alloy. The grid holds in place the active material with which the spaces in the grid are filled and distributes the current evenly to all parts of the plate.

When the paste is dry, the plates are given a forming charge. They are formed by immersing them in electrolyte and passing current through them in the proper direction to change the paste to lead peroxide for the positive plates and to sponge lead for the negative plates. This type of plate takes less time to manufacture and is relatively light in weight compared to the Plante spun-lead plates, which have a more rugged and durable construction.

IRONCLAD PLATE

The ironclad plate is used extensively in submarine batteries because it has a long life. The positive ironclad plate (fig. 2-10 (A)) is quite different from the pasted plate. It consists of several slotted hard-rubber tubes filled with active material that is similar to the material used in the pasted plate. Extending through the center of each tube is a core of lead antimony, which is firmly anchored in the paste by means of radial fins that are equally spaced along the core. The core, which is lead-burned to the top and bottom of the frame, serves primarily as a conductor for the electric current and strengthens the plate. Lead-antimony cores form the

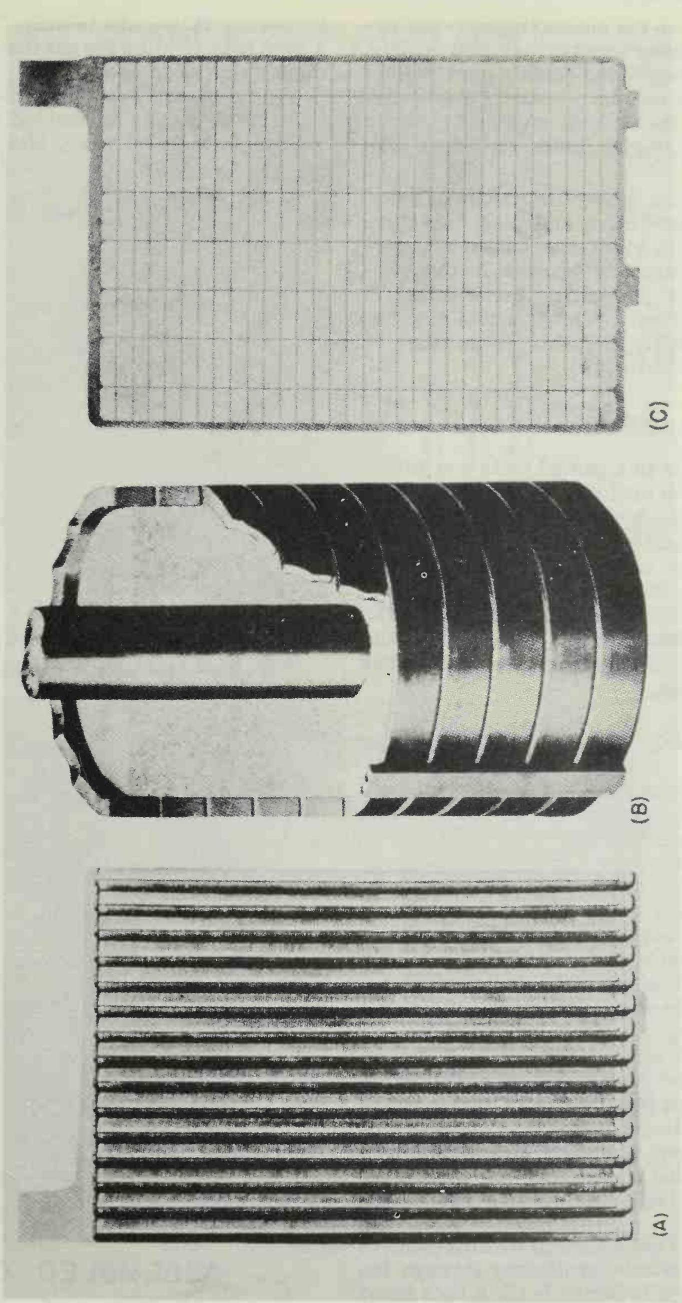


Figure 2-10.—Ironclad plate construction.

grids that comprise the conducting network between the hard-rubber tubes of the positive plate.

The hard-rubber tubes contain narrow horizontal slots to permit the passage of electrolyte through them so that it may come into contact with the active material inside the tubes (fig. 2-10 (B)).

The slotted tubes prevent the washing away, or shedding, of the active material. Each tube has two full-length ribs--one on each side--which keep the separators (spacers) from covering the slots and preventing the electrolyte from circulating freely. The ironclad negative plates are essentially the same as the negative pasted plates (fig. 2-10 (C)).

GOULD PLATE

The Gould Plate is a pasted plate that differs very little from the ordinary positive and negative pasted plates. A glass-wool mat directly over the positive plate holds the active material in place. Rubber or wood separators are used as in other batteries. The glass-wool mat prevents shedding amd makes the Gould battery almost as durable as the ironclad battery. Hence the Gould battery is used extensively in both submarines and surface vessels.

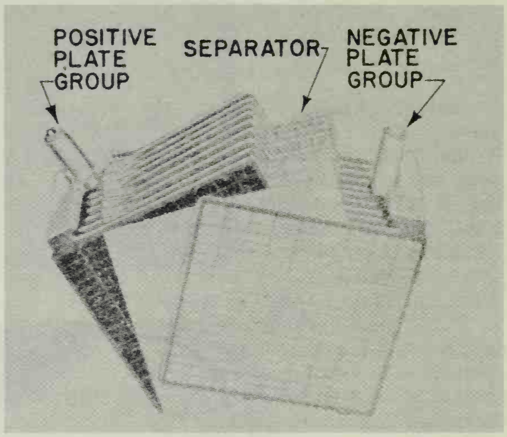
LEAD-ACID CELL ELEMENT

The plates are formed into positive and negative groups. When these groups are assembled, they become a cell element (fig. 2-11). The number of negative plates is always one more than the number of positive plates so that both sides of each positive plate are acted upon chemically. The active material on the positive plates expands and contracts as the battery is charged and discharged. The expansion and contraction must be kept the same on both sides of the plates to prevent buckling.

Separators of wood, rubber, or glass are placed between the positive and negative plates to act as insulators (fig. 2-11). These separators are grooved vertically on one side and are smooth on the other. The grooved side is placed next to the positive plate to permit free circulation of the electrolyte around the active material.

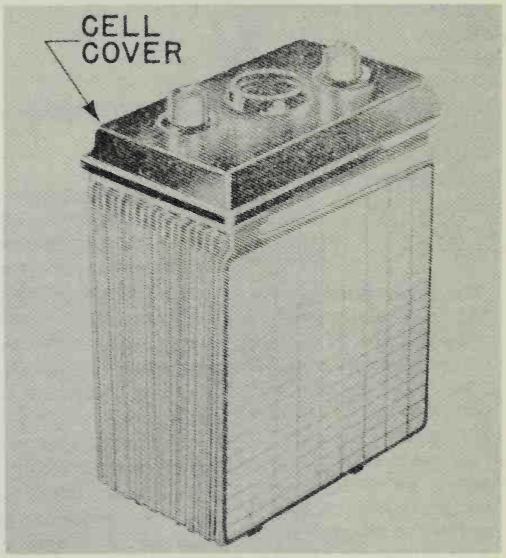
An assembled lead-acid cell with the positive and negative terminals projecting through the cell cover is shown in figure 2-12. A hole fitted with a filler cap is provided in each cell cover to permit filling and testing. The filler cap has a vent hole to allow the gas that forms in the cell during charge to escape.

The ordinary 6-volt portable storage battery consists of 3 cells assembled in a molded hard-rubber (monobloc) case. Metal cannot be used



CELL ELEMENT PARTLY ASSEMBLED

Figure 2-11.—Partly assembled cell element.



ASSEMBLED CELL

Figure 2-12.—Assembled lead-acid cell.

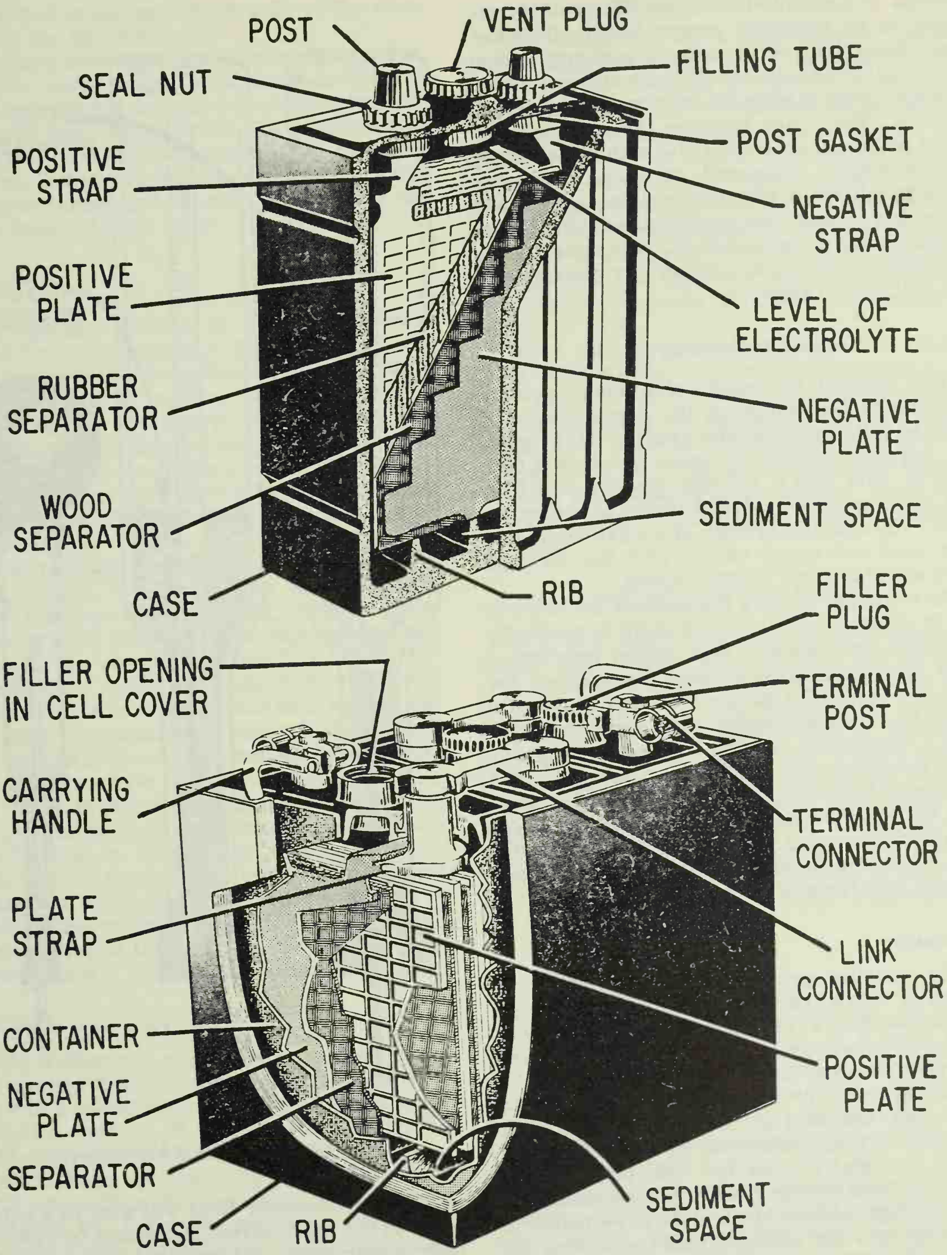

POST
VENT PLUG
SEAL NUT
FILLING TUBE
POST GASKET
POSITIVE STRAP
NEGATIVE STRAP
POSITIVE PLATE
LEVEL OF ELECTROLYTE
RUBBER SEPARATOR
NEGATIVE PLATE
WOOD SEPARATOR
SEDIMENT SPACE
CASE
RIB
FILLER PLUG
FILLER OPENING IN CELL COVER
TERMINAL POST
CARRYING HANDLE
TERMINAL CONNECTOR
PLATE STRAP
LINK CONNECTOR
CONTAINER
POSITIVE PLATE
NEGATIVE PLATE
SEPARATOR
CASE
RIB
SEDIMENT SPACE

Figure 2-13.—Lead-acid cell and battery.

because of the acid electrolyte. Each cell is contained in an acidproof compartment within the case. The cells are connected in series by means of lead-alloy connectors that are attached to the terminal posts of adjacent cells by a lead-burning process. The space between the case and the edges of the cell covers is filled with an acidproof battery-sealing compound, or pitch. This compound is a blend of bituminous materials that are processed so that they remain solid at high temperatures and do not crack at low temperatures.

Figure 2-13 shows a cutaway view of a lead-acid cell and a battery.

SPECIFIC GRAVITY

The ratio of the weight of a certain volume of liquid to the weight of the same volume of water is called the specific gravity of the liquid. The specific gravity of pure water is 1.000. Sulfuric acid has a specific gravity of 1.830; thus sulfuric acid is 1.830 times as heavy as water. The specific gravity of a mixture of sulfuric acid and water varies with the strength of the solution from 1.000 to 1.830.

As a storage battery discharges, the sulfuric acid is depleted and the electrolyte is gradually converted into water. This action provides a guide in determing the state of discharge of the lead-acid cell. The electrolyte that is usually placed in a lead-acid battery has a specific gravity of 1.350 or less. Generally, the specific gravity of the electrolyte in Navy portable batteries is adjusted between 1.210 and 1.220. On the other hand the specific gravity of the electrolyte in submarine batteries when charged is from 1.250 to 1.265, while in aircraft batteries when fully charged it is from 1.285 to 1.300.

Hydrometer

The specific gravity of the electrolyte is measured with a hydrometer. In the syringe-type hydrometer (fig. 2-14), part of the battery electrolyte is drawn up into a glass tube by means of a rubber bulb at the top.

The hydrometer float consists of a hollow glass tube weighted at one end and sealed at both ends. A scale calibrated in specific gravity is laid off axially along the body (stem) of the tube. The hydrometer float is placed inside the glass syringe and the electrolyte to be tested is drawn up into the syringe, thus immersing the hydrometer float into the solution. When the syringe is held approximately in a vertical position, the hydrometer float will sink to a certain level in the electrolyte. The extent to which the hydrometer stem protudes above the level of the liquid depends upon the specific gravity of the solution. The reading on the stem at the surface

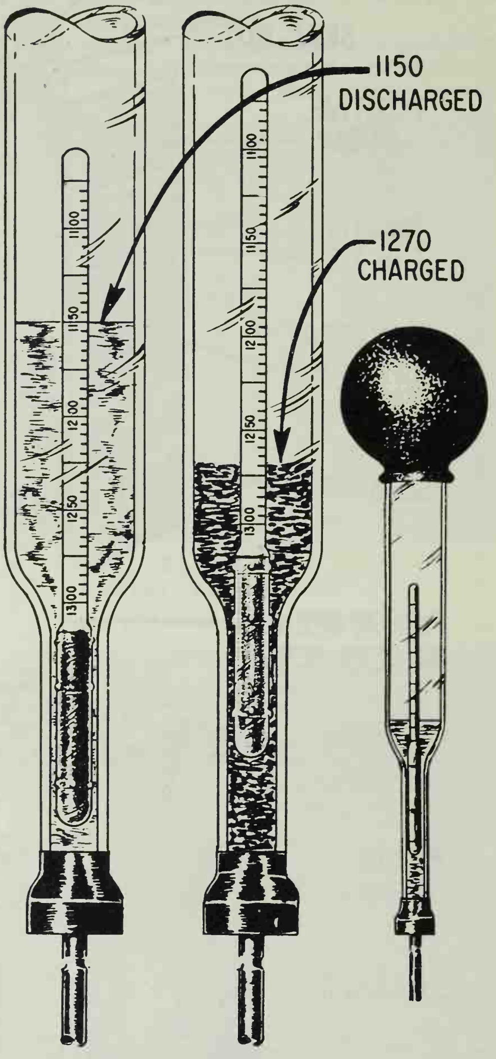


Figure 2-14.—Type-B hydrometer.

of the liquid is the specific gravity of the electrolyte in the syringe.

The Navy uses two types of hydrometer bulbs, or floats, each having a different scale. The type-A hydrometer is used with submarine batteries and has two different floats with scales from 1.060 to 1.240 and from 1.120 to 1.300. The type-B hydrometer is used with portable storage batteries and aircraft batteries. It has a scale from 1.100 to 1.300.

Corrections

The specific gravity of the electrolyte is affected by its temperature. The electrolyte expands and becomes less dense when heated and its specific gravity reading is lowered. On the other hand, the electrolyte contracts and becomes denser when cooled and its specific gravity reading is raised. In both cases the electrolyte may be from the same fully charged storage cell. Thus, the effect of temperature is to distort the readings.

All Navy standard storage batteries use 80°F. as the normal temperature to which specific gravity readings are corrected. To correct the specific gravity reading of a storage battery, add 1 point to the reading for each 3° F. above 80° and subtract 1 point for each 3° F. below 80°. The electrolyte in a cell should be at the normal level when the reading is taken. If the level is below normal, there will not be enough fluid drawn into the tube to cause the float to rise. If the level is above normal, there is too much water, the electrolyte is weakened, and the reading is too low. A hydrometer reading is inaccurate if taken immediately after water is added because the water tends to remain at the top of the cell. When water is added, the battery should be charged for at least an hour to mix the electrolyte before a hydrometer reading is taken.

Adjusting Specific Gravity

Only authorized personnel on a repair ship or at a shore station should add acid to a battery. Acid with a specific gravity above 1.350 is never added to a battery. If the specific gravity of a cell is more than it should be, it can be reduced to within limits by removing some of the electrolyte and adding distilled water. The battery is charged for 1 hour to mix the solution, and then hydrometer readings are taken. The adjustment is continued until the desired true readings are obtained.

MIXING ELECTROLYTES

The electrolyte of a fully charged battery usually contains about 38 percent sulfuric acid by weight, or about 27 percent by volume. In preparing the electrolyte distilled water and sulfuric acid that meets Navy specifications are used. New batteries may be delivered with containers of concentrated sulfuric acid of 1.830 specific gravity or electrolyte of 1.400 specific gravity, both of which must be diluted with distilled water to make electrolyte of the proper specific gravity. The container used for diluting the acid should be made of glass, earthenware, rubber, or lead.

When mixing electrolyte, ALWAYS POUR ACID INTO WATER—never pour water into acid. Pour the acid slowly and cautiously to prevent excessive heating and splashing. Stir the solution continuously with a nonmetallic rod to mix the heavier acid with the lighter water and to keep the acid from sinking to the bottom. When concentrated acid is diluted, the solution becomes very hot.

TREATMENT OF ACID BURNS

If acid or electrolyte from a lead-acid battery comes into contact with the skin, the affected area should be washed as soon as possible with large quantities of fresh water, after which a salve such as vaseline, boric acid, or zinc ointment should be applied. If none of these salves are available, clean lubricating oil will suffice. When washing, large amounts of water should be used, since a small amount of water might do more harm than good in spreading the acid burn.

Acid spilled on clothing may be neutralized with dilute ammonia or a solution of baking soda and water.

CAPACITY

The capacity of a battery is measured in ampere-hours. As mentioned before, the ampere-hour capacity is equal to the product of the current in amperes and the time in hours during which the battery is supplying this current. The ampere-hour capacity varies inversely with the discharge current. The size of a cell is determined generally by its ampere-hour capacity. The capacity of a cell depends upon many factors, the most important of which are (1) the area of the plates in contact with the electrolyte; (2) the quantity and specific gravity of the electrolyte; (3) the type of separators; (4) the general condition of the battery (degree of sulfating, plates buckled, separators warped, sediment in bottom of cells, and so forth); and (5) the final limiting voltage.

RATING

Navy storage batteries are rated according to their rate of discharge and ampere-hour capacity. All batteries, except Naval aircraft and those used for radio and sound systems, are rated according to a 10-hour rate of discharge--that is, if a fully charged battery is completely discharged during a 10-hour period, it is discharged at the 10-hour rate. Thus if a battery can deliver 40 amperes continuously for 10 hours, the battery has a rating of 40 x 10, or 400 ampere-hours. Thus the 10-hour rating is equal to the average current that a battery is capable of supplying without interruption for an interval of 10 hours. (NOTE: Aircraft batteries are rated according to a 2-hour rate of discharge.)

All Navy standard batteries deliver 100 percent of their available capacity if discharged in 10 hours or more, but they will deliver less than their available capacity if discharged at a faster rate. The faster they discharge, the less ampere-hour capacity they have.

The low-voltage limit, as specified by the manufacturer, is the limit beyond which very little useful energy can be obtained from a battery. For example, at the conclusion of a 10-hour discharge test on a Navy portable battery, the closed-circuit voltmeter reading is about 1.75 volts per cell and the specific gravity of the electrolyte is about 1.060. At the end of a charge, its closed-circuit voltmeter reading, while the battery is being charged at the finishing rate, is between 2.4 and 2.6 volts per cell. The specific gravity of the electrolyte corrected to 80° F. is between 1.210 and 1.220. In climates of 40° F. and below, authority may be granted to increase the specific gravity to 1.280. Other batteries, of higher normal specific gravity, may also be increased.

TEST DISCHARGE

The test discharge is the best method of determining the capacity of a battery. Most battery switchboards are provided with the necessary equipment for giving test discharges. If proper equipment is not available, a tender, repair ship, or shore station may make the test. To determine the battery capacity, a battery is normally given a test discharge once every 6 months. Test discharges are also given whenever any cell of a battery after charge cannot be brought within 10 points of full charge, or when one or more cells is found to have less than normal voltage after an equalizing charge.

A test discharge must always be preceded by an equalizing charge. Immediately after the equalizing charge, the battery is discharged at its 10-hour rate until either (1) the total battery voltage drops to a value equal to 1.75 times the number of cells in series, or (2) the voltage of any individual cell drops to 1.65 volts, whichever occurs first. The rate of discharge should be kept constant throughout the test discharge. Because Navy standard batteries are rated at the 10-hour capacity, the discharge rate for a 175 ampere-hour battery is 175/10, or 17.5 amperes. If the temperature of the electrolyte at the beginning of the charge is not exactly 80° F., the time duration of the discharge must be corrected for the actual temperature of the battery.

A battery of 100-percent capacity discharges at its 10-hour rate for 10 hours before reaching its low-voltage limit. If the battery or one of its cells reaches the low-voltage limit before the 10-hour period has elapsed, the discharge is discontinued immediately and the percentage of capacity is determined from the equation:

$$C = \frac{H_a}{H_t} \times 100, \qquad (2\text{-}1)$$

where C is the percentage of ampere-hour capacity available, H_a the total hours of discharge, and H_t the total hours for 100-percent capacity. The date for each test discharge should be recorded on the storage battery record sheet.

For example, a 150-ampere-hour 6-volt battery delivers an average current of 15 amperes for 10 hours. At the end of this period the battery voltage is 5.25 volts. On a later test the same battery delivers an average current of 15 amperes for only 7 hours. The discharge was stopped at the end of this time because the voltage of the middle cell was found to be only 1.65 volts. The percentage of capacity of the battery is now $\frac{7}{10}$ x 100, or 70 percent. Thus, the ampere-hour capacity of this battery is reduced to 0.7 x 150 = 105 ampere hours.

STATE OF CHARGE

After a battery is discharged completely from full charge at the 10-hour rate, the specific gravity has dropped about 150 points to about 1.060. The number of points that the specific gravity drops per ampere-hour can be determined for each type of battery. For each ampere-hour taken out of a battery a definite amount of acid is removed from the electrolyte and combined with the plates.

For example, if a battery is discharged from full charge to the low-voltage limit at the 10-hour rate and if 100 ampere-hours are obtained with a specific gravity drop of 150 points, there is a drop of $\frac{150}{100}$, or 1.5 points per ampere-hour delivered. If the reduction in specific gravity per ampere-hour is known, the drop in specific gravity for this battery may be predicted for any number of ampere-hours delivered to a load. For example, if 70 ampere-hours are delivered by the battery at the 10-hour rate or any other rate or collection of rates, the drop in specific gravity is 70 x 1.5, or 105 points.

Conversely, if the drop in specific gravity per ampere-hour and the total drop in specific gravity are known, the ampere-hours delivered by a battery may be determined. For example, if the specific gravity of the previously considered battery is 1.210 when the battery is fully charged and 1.150 when it is partly discharged, the drop in specific gravity is 1,210 - 1,150, or 60 points, and the number of ampere-hours taken out of the battery is $\frac{60}{1.5}$, or 40 ampere-hours. Thus, the number of ampere-hours expended in any battery discharge can be determined from the following three items: (1) The specific gravity when the battery is fully charged; (2) the specific gravity after the battery has been discharged; and (3) the reduction in specific gravity per ampere-hour.

Voltage alone is not a reliable indication of the state of charge of a battery except when the voltage is near the low-voltage limit on discharge. During discharge the voltage falls. The higher the rate of discharge the lower will be the terminal voltage. Open-circuit voltage is of little value because the variation between full charge and complete discharge is so small—only about 0.1 volt per cell. However, abnormally low voltage does indicate injurious sulfation or some other serious deterioration of the plates.

TYPES OF CHARGES

The following types of charges may be given to a storage battery, depending upon the condition of the battery: (1) Initial charge, (2) normal charge, (3) equalizing charge, (4) floating charge, and (5) emergency charge.

Initial Charge

When a new battery is shipped dry, the plates are in an uncharged condition. After the electrolyte has been added, it is necessary to convert the plates into the charged condition. This is accomplished by giving the battery a long low-rate INITIAL CHARGE. The charge is given in accordance with the manufacturer's instructions, which are shipped with each battery. If the manufacturer's instructions are not available, reference should be made to the detailed instruction in current bureau directives.

Normal Charge

A normal charge is a routine charge that is given in accordance with the nameplate data during the ordinary cycle of operation to restore the battery to its charged condition. The following steps should be observed:

1. Determine the starting and finishing rate from the nameplate data.
2. Add water, as necessary, to each cell.
3. Connect the battery to the charging panel and make sure the connections are clean and tight.
4. Turn on the charging circuit and set the current through the battery at the value given as the starting rate.
5. Check the temperature and specific gravity of pilot cells hourly.
6. When the battery begins to gas freely, reduce the charging current to the finishing rate.

A normal charge is complete when the specific gravity of the pilot cell, corrected for temperature, is within 5 points (0.005) of the specific gravity obtained on the previous equalizing charge.

Equalizing Charge

An equalizing charge is an extended normal charge at the finishing rate. It is given periodically to insure that all the sulfate is driven from the plates and that all the cells are restored to a maximum specific gravity. The equalizing charge is continued until the specific gravity of all cells, corrected for temperature, shows no change for a 4-hour period. Readings of all cells are taken every half hour.

Floating Charge

A battery may be maintained at full charge by connecting it across a charging source that has a voltage maintained within the limits of from 2.13 to 2.17 volts per cell of the battery. In a floating charge the charging rate is determined by the battery voltage rather than by a definite current value. The voltage is maintained between 2.13 and 2.17 volts per cell with an average as close to 2.15 volts as possible.

Emergency Charge

An emergency charge is used when a battery must be recharged in the shortest possible time. The charge starts at a much higher rate than is normally used for charging. It is seldom used because spare batteries are provided for all battery-operated equipment and this type charge may be harmful to the battery.

CHARGING RATE

The charging rate of every Navy storage battery is given on the battery nameplate. If the available charging equipment does not have the desired charging rates, the nearest available rates should be used. However, the rate should never be so high that violent gassing occurs. NEVER ALLOW THE TEMPERATURE OF THE ELECTROLYTE IN ANY CELL TO RISE ABOVE 125° F.

CHARGING TIME

The charge must be continued until the battery is fully charged. Frequent readings of specific gravity should be taken during the charge. These readings should be corrected to 80°F. and compared with the reading taken before the battery was placed on charge. If the rise in specific gravity in points per ampere-hour is known, the approximate time in hours required to complete the charge is

$$\frac{\text{rise in specific gravity in points to complete charge}}{\text{rise in specific gravity in points per ampere-hour} \times \text{charging rate in amperes}}$$

GASSING

When a battery is being charged, a portion of the energy is dissipated in the electrolysis of the water in the electrolyte. Thus, hydrogen is released at the negative plates and oxygen at the positive plates. These gases bubble up through the electrolyte and collect in the air space at the top of the cell. If violent gassing occurs when the battery is first placed on charge, the charging rate is too high. If the rate is not too high, steady gassing, which develops as the charging proceeds, indicates that the battery is nearing a fully charged condition. A mixture of hydrogen and air can be dangerously explosive. No smoking, electric sparks, or open flames should be permitted near charging batteries.

Nickel-Cadmium Cell

The nickel-cadmium cell is an alkaline storage cell. It is used in aircraft and in the Nike and Corporal guided missiles, and may be installed aboard ship in the foreseeable future. The construction and general arrangement of the cell are similar to that of the lead-acid cell. The negative plate assembly is a cadmium-oxide compound; the positive plate assembly is a nickel-oxide compound; and the electrolyte is a 30 percent solution of potassium hydroxide (KOH). Separators between the positive and negative groups prevent internal short circuits. The cell components are assembled in a single plastic jar. The battery case is of fabricated steel. A 6-volt battery contains 5 series-connected cells. When fully charged, the cell voltage ranges from 1.39 to 1.45 volts.

The nickel-cadmium battery used in some naval aircraft is interchangeable with the present aviation type lead-acid batteries. The nickel-cadmium and lead-acid batteries have capacities that are comparable at normal discharge rates, but at high discharge rates nickel-cadmium batteries have a higher capacity. The lead-acid aircraft battery is comprised of 12 cells with a nominal cell voltage of 2 volts, while the nickel-cadmium battery contains 20 cells with a nominal voltage of 1.4 volts per cell.

CHARGING

The effect of the charging current is to change the active material of the negative plate (cadmium-oxide) to metallic cadmium (CdO to Cd). The active material of the positive plate (nickel-oxide) is changed to a higher state of oxidation (NiO to Ni_2O_3). As long as the charging current continues, this action occurs until both materials are completely converted. Toward the end of the charging process and during overcharge, the cell will gas due to the electrolysis of the water in the electrolyte. This action liberates 4 atoms of hydrogen gas ($2H_2$) at the negative plate for every 2 atoms of oxygen gas (O_2) liberated at the positive plate. The amount of gas liberated depends on the charging rate.

The electrolyte does not enter into any chemical reaction with the positive or negative plates. It acts simply as a conductor of current between the plates, and its specific gravity does not vary appreciably with the amount of charge. The effect of the reactions during charge is a transfer of oxygen from the negative to the positive plates. In this respect the nickel-cadmium storage battery is similar to the lead-acid storage battery. Unlike the lead-acid storage battery the specific gravity of the electrolyte remains constant, except at the end of a charge or on overcharge, when it increases because of the electrolysis of the water. The proper specific gravity can be obtained by adding distilled water.

Nickel-cadmium batteries can be charged by the (1) constant voltage, (2) constant current, and (3) stepped constant-current methods. The most efficient performance is obtained when the charging rate is such that 140 percent of the rated ampere-hour capacity of the cell is delivered to the cell within a 3-hour interval.

DISCHARGING

When the cell is connected to an external circuit containing a resistance, the chemical action which occurs is the reverse to that of the charging process. The negative plate gradually regains oxygen (Cd to CdO), and the positive plate gradually loses oxygen (Ni_2O_3 to NiO); that is, the action during discharge effects a transfer of oxygen from the positive to the negative plates. There is no gassing on discharge due to the interchange of oxygen. The discharge process is the conversion of the chemical energy of the plates into electrical energy. The rate at which this conversion occurs is determined by the external resistance, or load, to which the battery is connected. The internal resistance of the cell is extremely low because of the cell construction.

The nickel-cadmium battery is smaller and weighs less than the comparable lead-acid battery. There is little or no local action, and the positive plates do not shed, or flake off, as do the positive plates in the lead-acid cell. The battery life is from 10 to 15 years with constant capacity over the entire period, and satisfactory operation can be obtained over a temperature range from -65° F. to 165° F.

Silver-Zinc Batteries

Silver-zinc batteries are presently used in guided missiles. These batteries are made up of cells that are classed as "reserve cells." As stated previously, a reserve cell is one which is maintained in the dry state until power is needed. At this time, the cell is activated by adding the electrolyte solution. Once the solution has been added, the battery requires no further charging. However, once activated, the silver-zinc battery must be used immediately because it has an extremely short shelf life. This battery is also quite expensive, due to its silver content.

The physical construction of these batteries is such that they are able to withstand high accelerations and to operate effectively in spite of the shock, vibration, and extreme temperature variations present in missile flight. Other advantages also tend to offset the cost and shelf-life restrictions. Two of the major advantages are (1) the high power-to-weight ratio of silver-zinc batteries and (2) their high discharge rate while maintaining a nearly flat voltage. That is, they are able to expend their energy at a high rate over a short period of time, as in the brief flight of a missile.

In the charged or "ready" state, the positive electrode material is silver peroxide, Ag_2O_2. The negative electrode is zinc, Zn, and the electrolyte is mainly potassium hydroxide, KOH. In discharging, the silver peroxide changes to a lower state of oxidation, becoming silver oxide, Ag_2O. In giving up oxygen atoms, the silver peroxide also loses electrons, thus becoming positive. The zinc electrode, in oxidizing (absorbing oxygen), accumulates excess electrons, and thus becomes negative. Water in the electrolyte is destroyed at the negative electrode, and formed at the positive electrode, with the net amount of water remaining constant.

QUIZ

1. The dry cell battery is a
   a. secondary cell
   b. polarized cell
   c. primary cell
   d. voltaic cell

2. The electrolyte of a lead-acid wet cell is
   a. sal ammoniac
   b. manganese dioxide
   c. sulfuric acid
   d. distilled water

3. A battery which can be restored after discharge is a
   a. primary cell
   b. galvanic cell
   c. dry cell
   d. secondary cell

4. Lead-acid battery plates are held together by a
   a. glass wool mat
   b. wood separators
   c. grid work
   d. hard rubber tube

5. When mixing electrolyte, always pour
   a. water into acid
   b. acid into water
   c. both acid and water into vat simultaneously
   d. any of the above are correct

6. When charging a battery, the electrolyte should never exceed a temperature of
   a. 125° F.
   b. 113° F.
   c. 80° F.
   d. 40° F.

7. The plates of a lead-acid battery are made of
   a. lead and lead dioxide
   b. lead and lead oxide
   c. silver and peroxide
   d. lead and lead peroxide

8. A battery is receiving a normal charge. It begins to gas freely. The charging current should
   a. be increased
   b. be decreased
   c. be cut off and the battery allowed to cool
   d. remain the same

9. A hydrometer reading is 1.265 at 92° F. The corrected reading is
   a. 1.229
   b. 1.261
   c. 1.269
   d. 1.301

10. In the nickel-cadmium battery, KOH is
    a. the positive plate
    b. the negative plate
    c. the electrolyte
    d. none of the above

11. When sulfuric acid, H_2SO_4, and water, H_2O, are mixed together, they form a
    a. gas
    b. compound
    c. mixture
    d. hydrogen solution

12. How many No. 6 dry cells are required to supply power to a load requiring 6 volts, if the cells are connected in series?
    a. Two
    b. Four
    c. Five
    d. Six

13. The ordinary 6-volt lead-acid storage battery consists of how many cells?
    a. Two
    b. Three
    c. Four
    d. Six

14. A fully charged aircraft battery has a specific gravity reading of
    a. 1.210 to 1.220
    b. 1.250 to 1.265
    c. 1.285 to 1.300
    d. 1.300 to 1.320

15. What is the ampere-hour rating of a storage battery that can deliver 20 amperes continuously for 10 hours?
    a. 20 ampere-hour
    b. 40 ampere-hour
    c. 200 ampere-hour
    d. 400 ampere-hour

16. The normal cell voltage of a fully charged nickel-cadmium battery is
    a. 2.0 volts
    b. 1.5 volts
    c. 1.4 volts
    d. 1.0 volts

17. The electrolyte in a mercury cell is
    a. sulfuric acid
    b. KOH
    c. potassium hydroxide, zincate, and mercury
    d. potassium hydroxide, water, and zincate

18. Concentrated sulfuric acid has a specific gravity of
    a. 1.285
    b. 1.300
    c. 1.830
    d. 2.400

19. The number of negative plates in a lead-acid cell is always
    a. one greater than the number of positive plates
    b. equal to the number of positive plates
    c. one less than the number of positive plates
    d. double the number of positive plates

20. A lead-acid battery is considered fully charged when the specific gravity readings of all cells taken at half-hour intervals show no change for
    a. four hours
    b. three hours
    c. two hours
    d. one hour

CHAPTER 3

THE SIMPLE ELECTRIC CIRCUIT

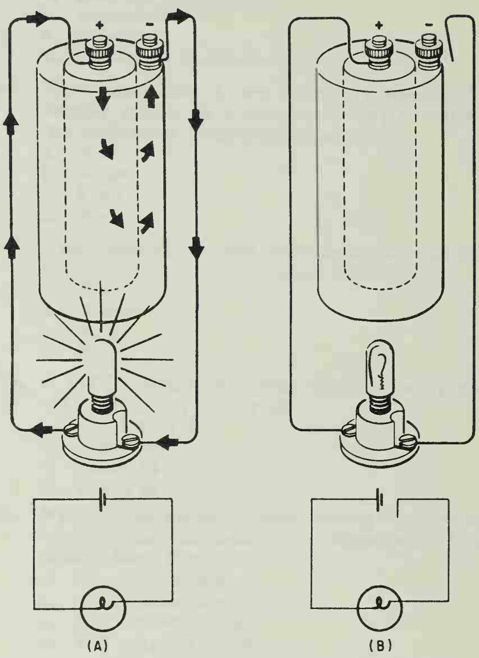
Whenever two unequal charges are connected by a conductor, a complete pathway for current flow exists. Current will flow from the negative to the positive charge. This was illustrated in chapter 1.

An electric circuit is a completed conducting pathway, consisting not only of the conductor, but including the path through the voltage source. Current flows from the positive terminal through the source, emerging at the negative terminal. As an example, a lamp connected by conductors across a dry cell forms a simple electric circuit. (Refer to fig. 3-1.)

Current flows from the (-) terminal of the battery through the lamp to the (+) battery terminal, and continues by going through the battery from the (+) to the (-) terminal. As long as this pathway is unbroken, it is a closed circuit and current will flow. However, if the path is broken at ANY point, it is an open circuit and no current flows.

Current flow in the external circuit is the movement of electrons in the direction indicated by the arrows (from the negative terminal through the lamp to the positive terminal). (See fig. 3-1 (A)). Current flow in the internal battery circuit is the simultaneous movement in opposite directions of positive hydrogen ions toward the positive terminal of the battery and negative ions toward the negative terminal.

A closed loop of wire (conductor) is not necessarily a circuit. A source of voltage must be included to make it an electric circuit. In any electric circuit where electrons move around a closed loop, current, voltage, and resistance are present. The physical pathway for current flow is actually the circuit. Its resistance controls the amount of current flow around the circuit. By knowing any two of the three quantities, such as voltage and current, the third (resistance) may be determined. This is done mathematically by the use of Ohm's law.



(A)
CLOSED CIRCUIT

(B)
OPEN CIRCUIT

Figure 3-1.—(A) Simple electric circuit (closed); (B) simple electric circuit (open).

Ohm's Law

In the 19th century, a German philosopher, Georg Simon Ohm, proved by experiment the constant proportionally between electric current and voltage in the simple electric circuit and published the results of his findings in 1826. Ohm's law is fundamentally linear and therefore simple. It is exact and applies to d-c circuits and devices in its basic form. In a modified form it may also be applied to a-c circuits. The unit of electrical resistance is called the OHM (designated by the Greek letter omega Ω) and finds wide application in the sources, loads, and conductors of electrical and electronics circuits.

MEANING OF OHM'S LAW

Ohm's law may be stated in words, as follows: THE INTENSITY OF THE CURRENT IN AMPERES IN ANY ELECTRIC CIRCUIT IS EQUAL TO THE DIFFERENCE IN POTENTIAL IN VOLTS ACROSS THE CIRCUIT DIVIDED BY THE RESISTANCE IN OHMS OF THE CIRCUIT.

Expressed as an equation, the law becomes

$$I = \frac{E}{R} \tag{3-1}$$

where I is the intensity of the current in amperes, E the difference in potential in volts, and R the resistance in ohms.

If any two of these quantities are known, the third may be found by applying equation (3-1).

For example, if the voltage across the lamp in figure 3-2 is 12 volts and the effective resistance of the lamp is 2 ohms, the current through is will be $\frac{12}{2}$, or 6 amperes. If the effective resistance of the lamp remains constant at 2 ohms, in accordance with Ohm's law, the current will double if the voltage doubles, or halve if the voltage halves. In other words the CURRENT THROUGH THE LOAD WILL VARY DIRECTLY WITH THE VOLTAGE ACROSS THE LOAD. Thus, if the voltage across the load is reduced to zero, the current will equal $\frac{0}{2}$, or 0 amperes. If the voltage across the load is increased in steps of 1 volt starting at zero and continuing to 12 volts, the current through the load becomes $\frac{1}{2}$ = 0.5 ampere; $\frac{2}{2}$ = 1.0 ampere; $\frac{3}{2}$ = 1.5 ampere; and so forth.

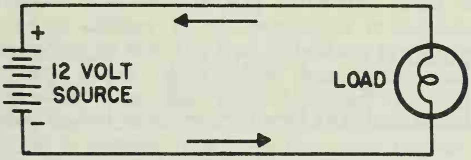


Figure 3-2.—Simple circuit.

The relation between current and voltage in this example is shown in figure 3-3 as a graph in which the voltage is plotted horizontally along the X axis to the right of the origin, and the corresponding values of current are plotted vertically along the Y axis above the origin.

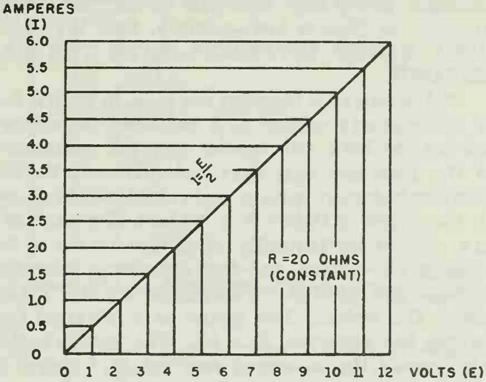


Figure 3-3.—Graph of voltage vs. current in a constant-resistance circuit.

The graph is a straight line, the equation of which is $I = \frac{E}{2}$. The constant, 2, represents the resistance in ohms of the circuit and is assumed not to change with the current in this example. This graph illustrates an important characteristic of the basic law—namely, the CURRENT VARIES DIRECTLY WITH THE APPLIED VOLTAGE IF THE RESISTANCE IS CONSTANT.

If the voltage across the load in figure 3-2 is maintained at a constant value of 12 volts, the current through the load will depend solely upon the effective resistance of the load. For example, if the resistance is 12 ohms, the current will be $\frac{12}{12}$, or 1 ampere. If the resistance is halved, the current will be doubled; if the resistance is doubled, the current will be halved. In other words, the current will vary inversely with the resistance.

If the resistance of the load is reduced in steps of 2 ohms starting at 12 ohms and continuing to 2 ohms, the current through the load becomes $\frac{12}{10} = 1.2$ amperes; $\frac{12}{8} = 1.5$ amperes; $\frac{12}{6} = 2$ amperes; and so forth. The relation between current and resistance in this example is expressed as a graph (fig. 3-4), whose equation is $I = \frac{12}{R}$. The numerator of the fraction represents a constant value of 12 volts in this example. As R approaches a small value the current approaches a very large value. The example illustrates a second equally important relation in Ohm's law—namely, that the CURRENT VARIES INVERSELY WITH THE RESISTANCE.

If the current through the load in figure 3-2 is maintained constant at 5 amperes, the voltage across the load will depend upon the resistance of the load and will vary directly with it. The relation between voltage and resistance is shown in the graph of figure 3-5. Values of resistance are plotted horizontally along the X axis to the right of the origin, and corresponding values of voltage are plotted vertically along the Y axis above the origin. The graph is a straight line having the equation $E = 5R$. The coefficient 5 represents the assumed current of 5 amperes which is constant in this example. Thus, a third important relation is illustrated—namely, that the VOLTAGE across a device VARIES DIRECTLY WITH THE EFFECTIVE RESISTANCE of the device provided the current through the device is maintained constant.

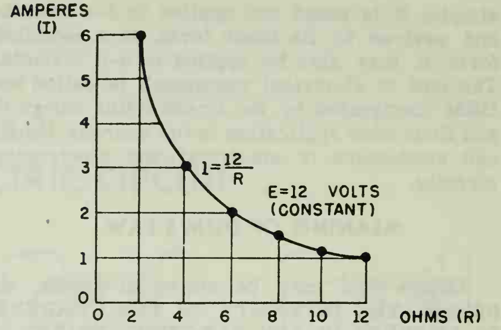


Figure 3-4.—Relation between current and resistance.

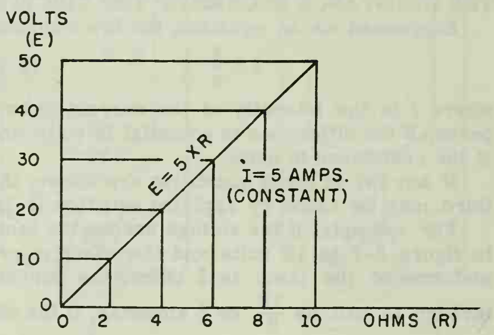


Figure 3-5.—Graph of voltage vs. resistance with constant current.

APPLYING OHM'S LAW

Equation (3-1) may be transposed to solve for the resistance if the current and voltage are known, or to solve for the voltage if the current and resistance are known. Thus, $R = \frac{E}{I}$ and $E = IR$. For example, if the voltage across a device is 50 volts and the current through it is 2 amperes, the resistance of the device will be $\frac{50}{2}$, or 25 ohms. Also, if the current through a wire is 3 amperes and the resistance of the wire is 0.5 ohm, the voltage drop across the wire will be 3 x 0.5, or 1.5 volts.

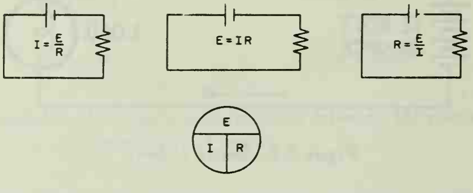


Figure 3-6.—Ohm's law in diagram form.

Equation (3-1) and its transpositions may be obtained readily with the aid of figure 3-6. The circle containing E, I, and R is divided into two parts with E above the line and IR below it. To determine the unknown quantity, first cover that quantity with a finger. The location of the remaining uncovered letters in the circle will indicate the mathematical operation to be performed. For example, to find I, cover I with a finger. The uncovered letters indicate that E is to be divided by R, or $I = \frac{E}{R}$. To find E, cover E. The result indicates that I is to be multiplied by R, or $E = IR$. To find R, cover R. The result indicates that E is to be divided by I, or $R = \frac{E}{I}$.

The beginning student is cautioned not to rely wholly on the use of this diagram when transposing simple formulas but rather to use it to supplement his knowledge of the algebraic method. Algebra is a basic tool in the solution of electrical problems and the importance of knowing how to use it should not be underemphasized or bypassed after the student has learned a shortcut method such as the one indicated in this figure.

Electric Power and Energy

POWER

Power, whether electrical or mechanical, pertains to the rate at which work is being done. Work is done whenever a force causes motion. If a mechanical force is used to lift or move a weight, work is done. However, force exerted WITHOUT causing motion, such as the force of a compressed spring acting between two fixed objects, does not constitute work.

Previously, you found that voltage is electrical force, and that voltage forces current to flow in a closed circuit. However, when voltage exists between two points, but current cannot flow, no work is done. This is similar to the spring under tension that produced no motion. When voltage causes electrons to move, work is done. The instantaneous RATE at which this work is done is called the electric power rate, and its measure is the watt.

A total amount of work may be done in different lengths of time. For example, a given number of electrons may be moved from one point to another in one second or in one hour, depending on the RATE at which they are moved. In both cases, total work done is the same. However, when the work is done in a short time, the wattage, or INSTANTANEOUS POWER RATE is greater than when the same amount of work is done over a longer period of time.

As stated, the basic unit of power is the WATT, and it is equal to the voltage across a circuit multiplied by current through the circuit. This represents the rate at any given instant at which work is being done in moving electrons through the circuit. The sympol P indicates electrical power. Thus, the basic power formula is $P = E \times I$. E is the voltage across and I is the current through the resistor or circuit whose power is being measured. The amount of power will change when either voltage or current, or both voltage and current change. This relation is shown with the graph and simple circuit in figure 3-7.

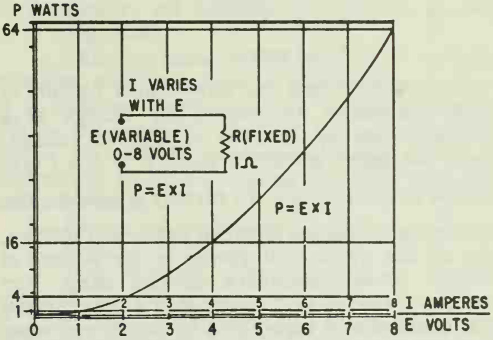


Figure 3-7.—Graph of power related to changing voltage and current.

The resistance is 1 ohm, and does not change. Voltage E is increased in steps of 1 volt from 0 to 8. By applying Ohm's law, the current I is determined for each step of voltage. For instance, when E is 4 volts, the current I is

$$I = \frac{E}{R} \tag{3-1}$$

$$I = \frac{4}{1}$$

$$I = 4 \text{ amperes.}$$

Power P, in watts, is determined by applying the basic power formula $P = E \times I$. When E is 1 volt, I is 1 ampere, so P is

$$P = E \times I$$
$$P = 1 \times 1$$
$$P = 1 \text{ watt}$$

However, when E is 2 volts, and I is 2 amperes, P becomes:

$$P = E \times I$$
$$P = 2 \times 2$$
$$P = 4 \text{ watts}$$

It is important to note that when voltage E was doubled from 1 volt to 2 volts, power P doubled TWICE from 1 watt to 4 watts. This occurred because the doubling of voltage caused a doubling of current, therefore power was doubled twice. This is shown as follows:

$$P = E \times I$$
$$P = E \times 2 \times I \times 2$$
$$P = (1 \times 2) \times (1 \times 2)$$
$$P = 2 \times 2$$
$$P = 4 \text{ watts.}$$

This shows that the power in a circuit of fixed resistance is caused to change at a SQUARE rate by changes in applied voltage. Thus, the basic power formula $P = E \times I$ may also be written $P = \frac{E^2}{R}$. To further illustrate the square-rate relation between power and voltage, note on the graph that power is the square of voltage (when resistance is one ohm). For instance, when E is 2 volts, P is 4 watts. When E is doubled to 4 volts, P is 16 watts, and when E is redoubled to 8 volts, P becomes 64 watts. When resistance is any value other than one ohm, power will not be the exact square of voltage in QUANTITY but it will still vary at a SQUARE RATE. That is, regardless of the value of resistance, so long as it is fixed, WHEN VOLTAGE DOUBLES, POWER DOUBLES TWICE. Also, WHEN THE VOLTAGE IS HALVED, POWER IS HALVED TWICE.

Another important relation may be seen by studying figure 3-7. Thus far power has been calculated with voltage and current ($P = E \times I$), and with voltage and resistance ($P = \frac{E^2}{R}$). Referring to figure 3-7, note that power also varies as the square of current just as it does with voltage. Thus, another formula for power, with current and resistance as its factors, is $P = I^2R$. Note that resistance R is a divisor in one formula ($P = \frac{E^2}{R}$), but is a multiplier in the other ($P = I^2R$). This is true because of substitutions in the original formula $P = E \times I$. That is, the Ohm's law equivalent of I is $\frac{E}{R}$. If this equivalent is substituted for I in the power formula $P = E \times I$, the results are as follows:

$$P = E \times I \qquad (3\text{-}2)$$
$$P = E \times \frac{E}{R}$$

$$P = \frac{E^2}{R} \qquad (3\text{-}3)$$

In addition, the Ohm's law equivalent of E is $I \times R$. If this equivalent is substituted for E, the power formula becomes

$$P = E \times I$$
$$P = (I \times R) \times I \qquad (3\text{-}4)$$
$$P = I^2R$$

In the foregoing discussion, and in figure 3-7, it was shown how variations of the voltage impressed across a fixed resistance caused variations in the circuit current and power. The following discussion refers to figure 3-8. In this circuit, the voltage E is fixed at 10 volts, and the resistance R is the variable factor. (The arrow through the resistance means it is variable).

When the resistance R is set at 1 ohm, the current I is 10 amperes, and the power is

$$P = I^2R \qquad (3\text{-}4)$$
$$P = (10^2) \times R$$
$$P = 100 \times 1$$
$$P = 100 \text{ watts}$$

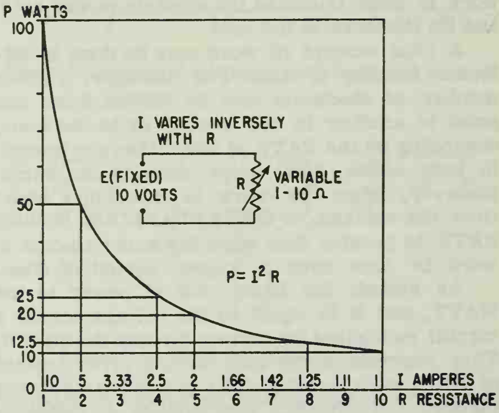


Figure 3-8.—Graph of power related to changing resistance and current.

When the resistance is DOUBLED to 2 ohms, this same calculation will show that power is HALVED to 50 watts, as the graph shows. Subsequent redoubling of the resistance to 4 and then to 8 ohms causes the power to be halved each time to 25 and 12-1/2 watts, respectively. Conversely, you should note the relation when starting with resistance at 10 ohms, with 10 watts of power. If resistance is HALVED to 5 ohms, power is DOUBLED to 20 watts.

In figures 3-7 and 3-8, current and power were caused to vary as a function of voltage, in one case, and of resistance in the other. In figure 3-9, however, current is held constant. This is done by raising or lowering voltage and resistance equally and directly with each other. The resulting variations in power are LINEAR with those changes. That is, power is changed step-for-step with voltage. The changing resistance maintains a constant current despite changes of voltage. At any point on the graph, voltage divided by resistance is 1 ampere. Had the current been allowed to vary, power would have changed at a curved, or SQUARE rate, instead of linearly as on the graph.

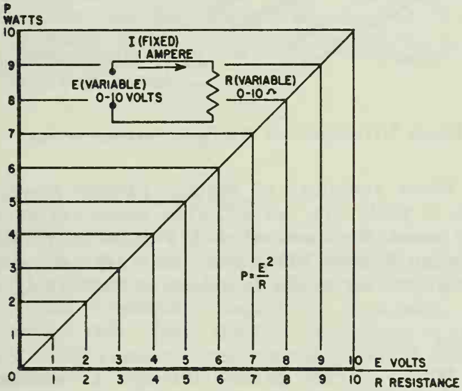


Figure 3-9.—Graph of power related to changing voltage and resistance.

Up to this point, four of the most important basic electrical quantities have been discussed. These are E, I, R, and P. It is of fundamental importance that you thoroughly understand the interrelation of these quantities. You should understand how any one of these quantities either controls or is controlled by the others in an electrical circuit. These relations are further explained in the treatment that follows. You should compare each statement carefully with its associated formula. Check each formula for correctness by applying it to the graphs in figures 3-7, 3-8, or 3-9. (The appropriate figure number is indicated after each of the following statements)

1. Power, as related to E and I: $P = EI$ (fig. 3-7).

   This formula states that P is the product of E multiplied by I, regardless of their individual values. If either E or I varies, P varies proportionally. If both E and I vary, P varies at a SQUARE rate.

2. Power, as related to I and R: $P = I^2R$ (fig. 3-8).

   This formula states that if R is held constant, and I is varied, P varies as the square of I, because I appears as a squared quantity (I^2) in the formula. Also, if I is held constant and R is varied, P varies directly and proportionally to R, because R is a MULTIPLIER in the formula.

3. Power, as related to E and R: $P = \frac{E^2}{R}$ (fig. 3-9).

   This formula states that if R is held constant, as E is varied, P varies as the square of E, because E appears as a squared quantity (E^2) in the formula. Also, if E is held constant and R is varied, P varies inversely but proportionally to R, because R is a DIVISOR in the formula.

In the preceding paragraph, P was expressed in terms of alternate pairs of the other three basic quantities E, I, and R. In practice, you should be able to express any one of the three basic quantities, as well as P, in terms of any two of the others. Figure 3-10 is a summary of twelve basic formulas you should know. The four quantities E, I, R, and P are at the center of the figure.

Adjacent to each quantity are three segments. Note that in each segment, the basic quantity is expressed in terms of two other basic quantities, and no two segments are alike.

RATING OF ELECTRICAL DEVICES BY POWER

Electrical lamps, soldering irons, and motors are examples of electrical devices that are rated in watts. The wattage rating of a device indicates the rate at which the device converts electrical energy into another form of energy, such as light, heat, or motion.

For example, a 100-watt lamp will produce a brighter light than a 75-watt lamp, because it converts more electrical energy into light

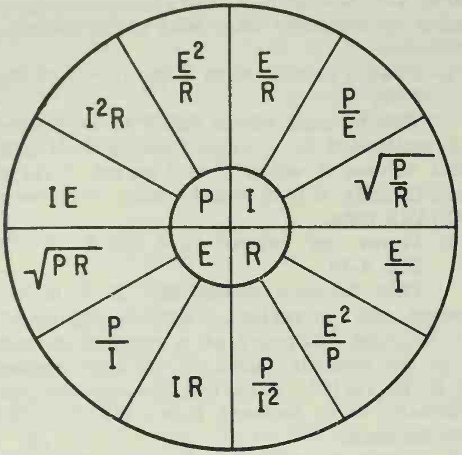


Figure 3-10.—Summary of basic formulas.

Electric soldering irons are of various wattage ratings, with the high-wattage irons changing more electrical energy to heat than those of low-wattage ratings.

If the normal wattage rating is exceeded, the equipment or device will overheat and probably be damaged. For example, if a lamp is rated 100 watts at 110 volts and is connected to a source of 220 volts, the current through the lamp will double. This will cause the lamp to use four times the wattage for which it is rated, and it will burn out quickly.

POWER CAPACITY OF ELECTRICAL DEVICES

Rather than indicate a device's ability to do work, its wattage rating may indicate the device's operating limits. These power limits generally are given as the maximum or minimum safe voltages and currents to which a device may be subjected. However, in cases where a device is not limited to any specific operating voltage, its limits are given directly in watts.

Resistors

A resistor is an example of such a device. It may be used in circuits with widely different voltages, depending on the desired current. However, the resistor has a maximum current limitation for each voltage applied to it. The product of the resistor's voltage and current at any time must not exceed a certain wattage.

Thus, resistors are rated in watts, in addition to their ohmic resistance. Resistors of the same resistance value are available in different wattage values. Carbon resistors, for example, are commonly made in wattage ratings of 1/3, 1/2, 1, and 2 watts. The larger the physical size of a carbon resistor, the higher its wattage rating, since a larger amount of material will absorb and give up heat more easily.

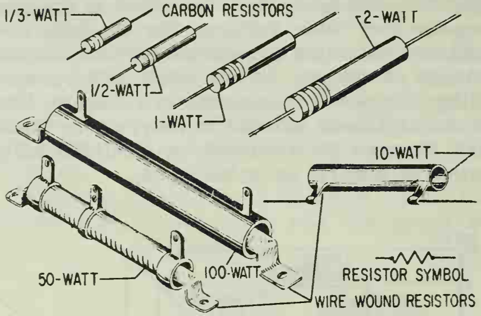


Figure 3-11.—Resistors of different wattage ratings.

When resistors of wattage ratings greater than 2 watts are needed, wire-wound resistors are used. Such resistors are made in ranges between 5 and 200 watts, with special types being used for power in excess of 200 watts.

Fuses

When current passes through a resistor, electric energy is transformed into heat, which raises the temperature of the resistor. If the temperature becomes too high, the resistor may be damaged. The metal wire in a wound resistor may melt, opening the circuit and interrupting current flow. This effect is used to an advantage in fuses.

Fuses are actually metal resistors with very low resistance values. They are designed to "blow out" and thus open a circuit when current exceeds the fuse's rated value.

When the power consumed by the fuse raises the temperature of its metal too high, the metal melts, or "blows." In service, fuses are generally connected as shown in figure 3-12.

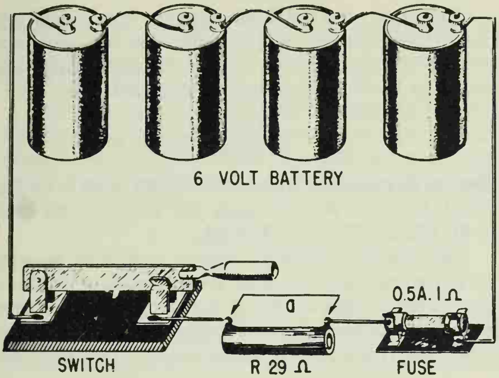


Figure 3-12.—Simple fused circuit.

Note that all current flowing through the load resistance of 29 ohms must also flow through the half-ampere fuse. Under normal conditions, the total resistance would be 29 + 1 = 30 ohms. If the switch were closed, the current I would be

$$I = \frac{E}{R}$$

$$I = \frac{6}{30}$$

$$I = 0.2 \text{ ampere}$$

This would be less than the rated current of the fuse, and it would not open. However, if the short conductor (a, fig. 3-12) were connected, the load resistance would be bypassed, or "shorted out." Only the fuse resistance of one ohm would remain in the circuit. Current would then be

$$I = \frac{E}{R}$$

$$I = \frac{6}{1}$$

$$I = 6 \text{ amperes}$$

Six amperes of current will cause the half-ampere fuse to open very quickly, because its wattage rating is greatly exceeded.

There are a great number of different types and sizes of fuses presently in use. Figure 3-13 shows three of the most common types.

ENERGY

Energy is defined as the ability to do work. Energy is expended when work is done, because

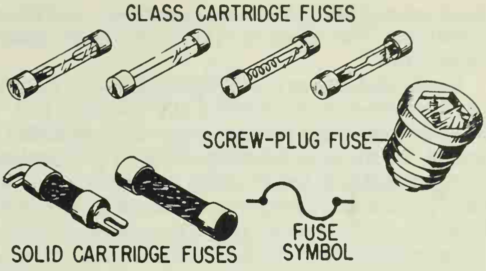


Figure 3-13.—Typical fuse types.

it takes energy to maintain a force when that force acts through a distance (works). The total energy expended to do a certain amount of work is equal to the working force multiplied by the distance through which the force moved to do the work. This is the mechanical definition.

In electricity, total energy expended is equal to the rate at which work is done, multiplied by the length of time the rate is measured. Essentially, energy W is equal to power P times time t.

An equation for energy is derived by multiplying both sides of equation (3-2) by the common factor of time, t, and equating the expression to the energy, W, as

$$W = Pt$$

$$W = EIt. \qquad (3\text{-}5)$$

Similarly, both sides of equations (3-3) and (3-4) may be multiplied by the time factor, t, and equated to the energy, W, as

$$W = \frac{E^2}{R}\,t, \qquad (3\text{-}6)$$

and

$$W = I^2Rt. \qquad (3\text{-}7)$$

In the energy equations (3-5), (3-6), and (3-7), E is in volts and I in amperes. If t is expressed in hours, W will be in watt-hours.

If t is expressed in seconds, W will be in watt-seconds or joules (1 joule is equal to 1 watt-second). Since $Q = It$ (where Q is in coulombs, I in amperes, and t in seconds), it is possible to substitute Q for It in equation (3-5) with the resulting expression for energy. Thus

$$W = QE \qquad (3\text{-}8)$$

where W is the energy in joules or watt-seconds, Q is the quantity in coulombs, and E is in volts. (As explained in chapter 1, Q is the symbol for coulombs. This is the measure of a QUANTITY of electrons. The Q is to electricity as the gallon is to water.)

Electrical energy is bought and sold in units of kilowatt-hours ($3{,}600 \times 10^3$ joules), and is totalized in large central generating stations in terms of megawatt-hours ($3{,}600 \times 10^6$ joules). For example, if the average demand over a 10-hour period is 70 megawatts, the total energy delivered is 70 x 10, or 700 megawatt-hours. This amount of energy is equivalent to $700 \times 1{,}000 = 700{,}000$ kilowatt-hours, or $700 \times 3{,}600 \times 10^6 = 2{,}520{,}000 \times 10^6$ joules. The most practical unit to use depends in part upon the magnitude of the quantity of energy involved, and in this example the megawatt-hour is appropriate.

Problems

Ohm's law for power calculations may be applied to a great many everyday problems wherever electricity is at work.

Consider one of the most common examples —that of the incandescent electric light. Incandescent lamps for use in constant-potential circuits in homes and factories are rated in volts and watts. How much current do they take? How much resistance do they possess? If high powered, they may draw several amperes; if low in wattage rating, they may take only a small fraction of an ampere. Specifically the current rating of a 100-watt 120-volt lamp is easily found by transposing equation (3-2) and solving for the current. Thus

$$I = \frac{P}{E} = \frac{100}{120} = 0.833 \text{ ampere.}$$

The resistance of this lamp during normal operation may be found by substituting the calculated value of current and the rated voltage in equation (3-1) and transposing for R—

$$R = \frac{120}{0.833} = 144 \text{ ohms.}$$

Thus, a 100-watt 120-volt lamp draws a current of 0.833 ampere and has a hot resistance of 144 ohms. How much does it cost to use this lamp 4 hours each evening for 30 days at 3.2 cents per kilowatt-hour? Surprising little, as seen by the calculation:

$$\text{Total kilowatt-hours} = Pt = \frac{100 \times 4 \times 30}{1{,}000} = 12,$$

$$\text{Total cost} = 3.2 \times 12 = 38.4 \text{ cents.}$$

Consider the cost to operate a window air conditioner rated at 120 volts and 9.4 amperes in use 10 hours a day for 30 days. Applying equation (3-2), the power in kilowatts is

$$P = \frac{EI}{1{,}000} = \frac{120 \times 9.4}{1{,}000} = 1.128 \text{ kw.}$$

The total kilowatt-hours are 1.128 x 30 x 10, or 338.4 kw.-hr. At 3.2 cents per kw.-hr. the cost is $0.032 x 338.4, or $10.83.

Household electric stoves require special circuits as may be seen from the magnitude of the current drawn by a 7.5-kw. 220-v. range with all burners turned on full. The current is found by transposing equation (3-2) as follows:

$$I = \frac{P}{E} = \frac{7{,}500}{220} = 34 \text{ amperes.}$$

Since most household branch circuits are not permitted to carry more than 20 amperes, the possibility of a 34-ampere load requires special circuits for the range. It is also important to note that the availability of the 220-volt service (rather than 110-volt service) permits the use of smaller conductors since current varies inversely with voltage for a given power rating. Thus a 7.5-kw. range rated at 110 volts would draw a maximum of $\frac{220}{110} \times 34$, or 68 amperes.

To further illustrate the inverse ratio between current and voltage for a given power rating, consider the current drawn by a 100-watt incandescent lamp having a voltage rating of 6 volts. Transposing equation (3-2) the current is

$$I = \frac{P}{E} = 16.6 \text{ amperes.}$$

This value of current is $\frac{120}{6}$, or 20 times the value required by a 120-volt lamp of the same wattage rating.

It is important to operate incandescent lamps within their voltage rating, since any appreciable over-voltage even for a short period reduces the life of the lamp a relatively large amount. For example, an increase in the voltage on a 25-watt 110-volt lamp from 110 volts to 140 volts will increase the current proportionately from $\frac{25}{110} = 0.228$ amperes to $\frac{140}{110} \times 0.228 = 0.290$ ampere. Since the power absorbed varies as the square of the applied voltage, increasing the applied voltage from 110 to 140 volts will increase the power to $\frac{(140)^2}{110}$, or 1.62 times the rated power. In a short time the lamp filament will burn out.

As another example illustrating the relation between the basic units, consider the current drawn by a 1,000-watt 120-volt electric flatiron. From equation (3-2) the current is found to be

$$I = \frac{P}{E} = \frac{1,000}{120} = 8.33 \text{ amperes.}$$

The hot resistance of this flatiron's heating element may be found by substituting the known values of current and voltage in equation (3-1) and solving for R. Thus

$$R = \frac{E}{I} = \frac{120}{8.33} = 14.4 \text{ ohms.}$$

The resistance of 14.4 ohms represents the operating resistance of the iron when it is carrying rated current. The resistance may also be calculated directly from equation (3-3) by substituting the values of voltage and power and transposing for R as follows:

$$R = \frac{E^2}{P} = \frac{(120)^2}{1,000} = 14.4 \text{ ohms.}$$

The appropriate equation depends upon what is given and what is to be found.

For example, find the total energy in watt-hours delivered by a 12-volt storage battery supplying an average current of 10 amperes for a 10-hour period. Applying equation (3-5),

$$W = EIt = 12 \times 10 \times 10 = 1,200 \text{ watt-hours.}$$

The product of amperes, hours, and volts is equal to watt-hours; and in this example, the battery is capable of furnishing electrical energy equivalent to 1,200 watt-hours, or 1.2 kilowatt-hours.

Another transposition of equation (3-3) may be used to solve the following problem: Find the voltage across, and the current through, a 100-ohm 500-watt resistor when it is carrying its rated load. Solving equation (3-3) for voltage in terms of the given values of power and resistance,

$$E = \sqrt{PR} = \sqrt{500 \times 100} = 224 \text{ volts.}$$

Thus, a 500-watt 100-ohm load will have a voltage of 224 volts across it. The current through the load may be found by transposing equation (3-4) and substituting the given values as follows:

$$I = \sqrt{\frac{P}{R}} = \sqrt{\frac{500}{100}} = 2.24 \text{ amperes.}$$

The power absorbed by the load may be checked by substituting the calculated value of current and the given value of resistance in equation (3-4), and solving as follows:

$$P = I^2R = (2.24)^2 \times 100 = 500 \text{ watts.}$$

The resistance of the load may be checked by transposing equation (3-1), substituting the calculated values of voltage and current, and solving for R as follows:

$$R = \frac{E}{I} = \frac{224}{2.24} = 100 \text{ ohms.}$$

You are urged to develop the habit of checking your work by using two or more equations to arrive at the same result. Two avenues of approach are more desirable than one since they tend to avoid mistakes that are frequently repeated in the single-approach method.

Current and voltage are important considerations in the operation of electric motors. Consider the power supplied to a large motor when it is drawing 125 amperes from a 600-volt d-c circuit. Applying equation (3-2),

$$P = EI = 600 \times 125 = 75,000 \text{ watts.}$$

This amount of power may be expressed in equivalent horsepower (746 watts = 1 horsepower) as $\frac{75,000}{746}$, or 100,2 horsepower. If the requirements of the load are such that the horsepower remains constant, then the input current will vary inversely with the applied voltage. Suppose, for example, that the voltage falls from 600 volts to 450 volts. The current required to maintain constant input power will be

$$I = \frac{P}{E} = \frac{75,000}{450} = 166 \text{ amperes.}$$

This current represents an increase of 41 amperes, or 32.8 percent, and probably will cause overheating of the motor. The condition is peculiar to electric motors and rotating machinery in general and represents a situation in which the effective load resistance varies as the square of the applied voltage ($R = \frac{E^2}{P}$).

The effective resistance offered by the motor to the flow of current when the voltage is 600 volts is

$$R = \frac{E}{I} = \frac{600}{125} = 4.8 \text{ ohms},$$

and when the voltage falls to 450 volts, it is decreased to $\frac{450}{166}$, or 2.7 ohms. A check on the effective resistance at 600 volts may be obtained by transposing equation (3-3) and substituting the values of E and P as follows:

$$R = \frac{E^2}{P} = \frac{(600)^2}{75{,}000} = 4.8 \text{ ohms.}$$

A similar check on the effective resistance at 450 volts is

$$R = \frac{E^2}{P} = \frac{(450)^2}{75{,}000} = 2.7 \text{ ohms.}$$

The tendency of motors to increase their input current when the supply voltage decreases does not apply to electrical loads such as resistors, heating units, electric lights, and so forth. Therefore the action described in the preceding example should not be assumed to apply indiscriminately without regard to the characteristics of the particular load being considered.

Applying the simple three-letter equations of this chapter to the solution of elementary problems in electricity is not difficult. However, the ease of solution may be misleading to the student with an inquiring mind. Your attempt to prove your answers with practical equivalent circuits may reveal more than one variable in the elementary circuit.

For example, you find that Ohm's law states that the current through an electric circuit is directly proportional to the applied voltage, yet when the voltage is increased (for example, on an incandescent lamp), the current increase is not in direct proportion to the voltage increase. The discrepancy is explained by the tendency of tungsten to increase its resistance with temperature. Thus an increase in filament voltage causes an increase in filament current and temperature. The increase in filament temperature causes an increase in filament resistance. Two variables now affect the circuit current instead of one. These variables are voltage and resistance instead of voltage alone.

For example, the current at 110 volts and 120 ohms is

$$I = \frac{E}{R} = \frac{110}{120} = 0.917 \text{ ampere.}$$

The current at 132 volts and 130 ohms is

$$I = \frac{132}{130} = 1.015 \text{ amperes.}$$

The increase in voltage is 132 - 110, or 22 volts, and the percent increase is $\frac{22 \times 100}{110}$, or 20 percent. The increase in resistance is 130 - 120, or 10 ohms, and the percent increase is $\frac{10 \times 100}{120}$, or 8.33 percent. The increase in current is 1.015 - 0.917, or 0.098 ampere, and the percent increase is $\frac{0.098 \times 100}{0.917}$, or 10.7 percent. Thus an increase in voltage of 20 percent is accompanied by an increase in current of only 10.7 percent. If the voltage had been the only variable the current would have followed it exactly—that is, an increase in voltage of 20 percent would have resulted in an increase in current of 20 percent. Instead, the current increased only 10.7 percent because the resistance increased 8.3 percent.

The equations themselves do not reveal the behavior of circuits. They do indicate, however, the numerical relation between the volt, ampere, ohm, and watt, and to that extent they contribute basic knowledge to the learner.

QUIZ

1. In which direction does current flow in an electrical circuit?

   a. - to + externally, + to - internally
   b. + to - externally, + to - internally
   c. - to + externally, - to + internally
   d. + to - externally, - to + internally

2. Given the formula: $P = E^2/R$, solve for E.

   a. $E = \sqrt{ER}$
   b. $E = \sqrt{PR}$
   c. $E = IR$
   d. $E = \sqrt{P/R}$

3. Resistance in the power formula equals
   a. $R = \sqrt{I/P}$
   b. $R = E/I$
   c. $R = \sqrt{P \times I}$
   d. $R = E^2/P$

4. One joule is equal to
   a. 1 watt second
   b. 10 watt seconds
   c. 1 watt minute
   d. 10 watt minutes

5. A lamp has a source voltage of 110 v. and a current of 0.9 amps. What is the resistance of the lamp?
   a. 12.22 Ω
   b. 122.2 Ω
   c. 0.008 Ω
   d. 0.08 Ω

6. In accordance with Ohm's law, the relationship between current and voltage in a simple circuit is that the
   a. current varies inversely with the resistance if the voltage is held constant
   b. voltage varies as the square of the applied e.m.f.
   c. current varies directly with the applied voltage if the resistance is held constant
   d. voltage varies inversely as the current if the resistance is held constant

7. The current needed to operate a soldering iron which has a rating of 600 watts at 110 volts is
   a. 0.182 a.
   b. 5.455 a.
   c. 18.200 a.
   d. 66.000 a.

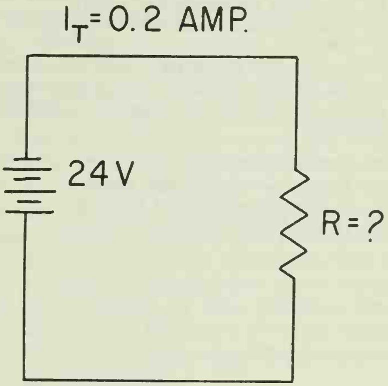
8. In electrical circuits, the time rate of doing work is expressed in
   a. volts
   b. amperes
   c. watts
   d. ohms

9. If the resistance is held constant, what is the relationship between power and voltage in a simple circuit?
   a. Resistance must be varied to show a true relationship
   b. Power will vary as the square of the applied voltage
   c. Voltage will vary inversely proportional to power
   d. Power will vary directly with voltage

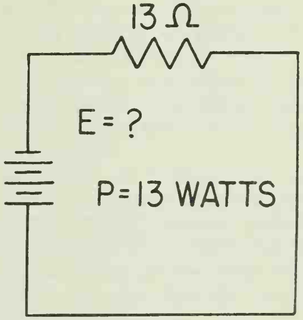
10. How many watts are there in 1 horsepower?
   a. 500
   b. 640
   c. 746
   d. 1,000

11. What formula is used to find watt-hours?
   a. $E \times T$
   b. $E \times I \times T$
   c. $E \times I \times \angle\theta$
   d. $E \times I^2$

12. What is the resistance of the circuit shown below?
   a. 4.8 Ω
   b. 12.0 Ω
   c. 48 Ω
   d. 120 Ω



13. In the figure below, solve for I_T
   a. 0.5 a.
   b. 1 a.
   c. 13 a.
   d. 169 a.



14. A simple circuit consists of one power source,
   a. and one power consuming device
   b. one power consuming device, and connecting wiring
   c. protective device, and control device
   d. one power consuming device, and protective device

15. The device used in circuits to prevent damage from overloads is called a
    a. fuse
    b. switch
    c. resistor
    d. connector

16. What happens in a series circuit when the voltage remains constant and the resistance increases?
    a. Current increases
    b. Current decreases
    c. Current remains the same
    d. Current increases by the square

17. Other factors remaining constant, what would be the effect on the current flow in a given circuit if the applied potential were doubled?
    a. It would double
    b. It would remain the same
    c. It would be divided by two
    d. It would be divided by four

18. Which of the following procedures can be used to calculate the resistance of a load?
    a. Multiply the voltage across the load by the square of the current through the load
    b. Divide the current through the load by the voltage across the load
    c. Multiply the voltage across the load by the current through the load
    d. Divide the voltage across the load by the current through the load

19. A cockpit light operates from a 24-volt d-c supply and uses 72 watts of power. The current flowing through the bulb is
    a. 0.33 amps
    b. 3 amps
    c. 600 amps
    d. 1,728 amps

20. If the resistance is held constant, what happens to power if the current is doubled?
    a. Power is doubled
    b. Power is multiplied by 4
    c. Power is halved
    d. Power is divided by 4

CHAPTER 4

DIRECT-CURRENT SERIES AND PARALLEL CIRCUITS

An electric circuit is a complete path through which electrons can flow from the negative terminal of the voltage source; through the connecting wires, or conductors; through the load, or loads; and back to the positive terminal of the voltage source. A circuit is thus made up of a voltage source, the necessary connecting conductors, and the effective load.

If the circuit is arranged so that the electrons have only ONE possible path, the circuit is called a SERIES CIRCUIT. If there are two or more paths supplied by a common voltage source, the circuit is called a PARALLEL CIRCUIT.

In any type of work that utilizes the effects of electron flow a knowledge of series and parallel circuits is desirable. None of the effects accompanying electron flow—for example, heating, lighting, or magnetic effects—would be possible without the use of electric circuits; and many electrical devices can be utilized more effectively if the operator has a knowledge of how they work. The purpose of this chapter is to give in simplified form conventional methods of calculating resistance in basic series and parallel circuits and to show how problems involving current, voltage, and power may be solved by the use of basic formulas. The next chapter is similar, except that more complex circuits are treated. In both chapters Ohm's Law or Kirchhoff's Laws are used as required to solve for various unknown values of current, voltage, or resistance.

Series Circuits

KIRCHHOFF'S VOLTAGE LAW APPLIED TO SERIES CIRCUITS

All conductors have resistance, and therefore a circuit made up of nothing but conductors would have some resistance, however small it might be. In circuits containing long conductors through which an appreciable amount of current is drawn the resistance of the conductors becomes important. However, for the purposes of this chapter the resistance of the connecting wires is neglected, and only the resistance of each resistor element (which may be any device that has resistance) is considered.

Kirchhoff's Law of Voltages states that the algebraic sum of all the voltages in any complete electric circuit is equal to zero. In other words, the sum of all positive voltages MUST BE equal to the sum of all negative voltages. For any voltage rise there must be an equal voltage drop somewhere in the circuit. The voltage rise (potential source) is usually regarded as the power supply, such as a battery. The voltage drop is usually regarded as the load, such as a resistor. The voltage drop may be distributed across a number of resistive elements, such as a string of lamps or several resistors. However, according to Kirchhoff's Law, the sum of their individual voltage drops MUST ALWAYS equal the voltage rise supplied by the power source.

The statement of Kirchhoff's Law can be translated into a truthful equation, from which many unknown circuit factors may be determined. (Refer to fig. 4-1.) Note that the source voltage E_s is equal to the sum of the three load voltages E_1, E_2, and E_3. In a formula, this would be written

$$E_s = E_1 + E_2 + E_3.$$

This formula may also be transposed to demonstrate that the algebraic sum of all the voltages is zero, as follows:

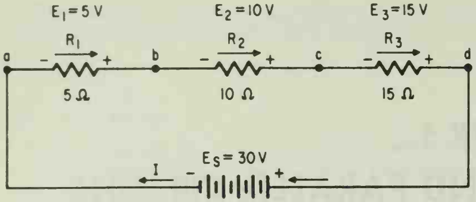


Figure 4-1.—Series circuit for demonstrating Kirchhoff's Voltage Law.

In order to solve problems applicable to figure 4-1, and others similar to it, the following procedure is suggested.

1. Note the polarity of the source e.m.f. (E_S) and indicate the electron flow around the circuit. Electron flow is out from the negative terminal of the source, through the load, and back to the positive terminal of the source. In the example being considered, the arrows indicate electron flow in a clockwise direction around the circuit.

2. To apply Kirchhoff's Law it is necessary to establish a voltage equation. The equation is developed by tracing around the circuit and noting the voltage absorbed (called voltage drop) across each part of the circuit encountered by the trace, and expressing the sum of these voltages according to the voltage law. It is important that the trace be made around a closed circuit, and that it encircle the circuit only once. Thus, a point is arbitrarily selected at which to start the trace. The trace is then made, and upon completion, the terminal point coincides with the starting point.

3. Sources of e.m.f. are preceded by a PLUS sign if in tracing through the source the first terminal encountered is positive; if the first terminal is negative, the e.m.f. is preceded by a MINUS sign.

4. Voltage drops along wires and across resistors (loads) are preceded by a minus sign if the trace is in the assumed direction of electron flow; if in the opposite direction the sign is plus.

5. If the assumed direction of electron flow is incorrect, the error will be indicated by a minus sign preceding the current, in solving for circuit current. The magnitude of the current will not be affected.

The preceding rules may be applied to the example of figure 4-1 as follows:

1. The left terminal of the battery is negative, the right terminal is positive, and electron flow is clockwise around the circuit.

2. The trace may arbitrarily be started at the positive terminal of the source and continued clockwise through the source to its negative terminal. From this point the trace is continued around the circuit to *a, b, c, d,* and back to the positive terminal, thus completing the trace once around the entire closed circuit.

3. The first term of the voltage equation is $+E_S$.

4. The second, third, and fourth terms are respectively, $-E_1$, $-E_2$, and $-E_3$. Their algebraic sum is equated to zero as follows:

$$E_s - E_1 - E_2 - E_3 = 0.$$

Transposing the voltage equation and solving for E_S,

$$E_s = E_1 + E_2 + E_3.$$

Since $E = IR$ from Ohm's law, the voltage drop across each resistor may be expressed in terms of the current and resistance of the individual resistor as follows:

$$E_s = IR_1 + IR_2 + IR_3,$$

where R_1, R_2, and R_3 are the resistances, E_S is the source voltage, and I is the circuit current.

E_S may be expressed in terms of the circuit current and total resistance as IR_t. Substituting IR_t for E_S, the voltage equation becomes,

$$IR_t = IR_1 + IR_2 + IR_3.$$

Since there is only one path for current in the series circuit, the total current is the same in all parts of the circuit. Dividing both sides of the voltage equation by the common factor, I, an expression is derived for the total resistance of the circuit.

$$R_t = R_1 + R_2 + R_3.$$

Therefore, in series circuits THE TOTAL RESISTANCE IS THE SUM OF THE RESISTANCES OF THE INDIVIDUAL PARTS OF THE CIRCUIT.

In the example of figure 4-1, the total resistance is

$$5 + 10 + 15 = 30 \text{ ohms.}$$

The total current may be found by applying the equation

$$I_t = \frac{E_t}{R_t} = \frac{30}{30} = 1 \text{ ampere.}$$

The power absorbed by resistor R_1 is I^2R_1, or $1^2 \times 5 = 5$ watts. Similarly the power absorbed by R_2 is $1^2 \times 10 = 10$ watts, and the power absorbed by R_3 is $1^2 \times 15 = 15$ watts. The total power absorbed is the arithmetic sum of the power of each resistor, or $5 + 10 + 15 = 30$ watts. The value is also calculated by $P_t = E_tI_t = 30 \times 1 = 30$ watts.

More than one voltage source may be used in a series circuit. If the polarities of the sources are such that they aid each other, they are simply added together, and the net result is the same as if a single source of higher voltage had been used. If the polarities of the sources are such that one or more of them tend to cancel or "buck out" the effect of the others, then the net result is the difference between the source voltages that would cause the circuit current to flow in one direction and the source voltages that cause it to flow in the opposite direction.

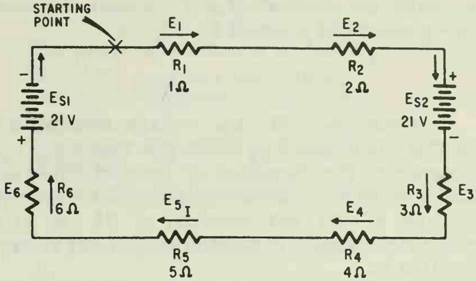
Actually, the current could be assumed to flow in either direction as long as the minus sign is placed before each voltage drop (when the circuit is traced in the direction of the assumed current flow) and the proper sign (the one encountered as the source is approached in the circuit) is placed before all voltage sources. As mentioned previously, if the resultant circuit current has a negative sign it merely means that the assumed direction of current flow is incorrect.

Kirchhoff's Voltage Law is readily applied in solving series circuit problems. In many cases, it is the most practical method that may be used. For example, in figure 4-2, Kirchhoff's Voltage Law is used to solve for current, I; and when this has been determined, the other unknown values may be determined by Ohm's Law or the associated power formulas.

In figure 4-2 (A), the two voltage sources are aiding each other; that is, the polarities are connected so that each source tends to make the current flow clockwise around the circuit. Starting at the left terminal of $R1$ and proceeding clockwise around the circuit, the voltage equation is,

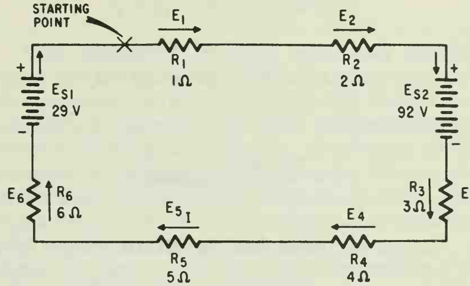
$$-E_1 - E_2 + E_{s2} - E_3 - E_4 - E_5 - E_6 + E_{s1} = 0.$$

Expressing the voltage drops around the circuit in terms of current and resistance, and the given values of source voltage, the equation becomes,



SOURCES AIDING

(A)



SOURCES BUCKING

(B)

Figure 4-2.—Application of Kirchhoff's Law to series circuits.

$$\begin{aligned} -I - 2I + 21 - 3I - 4I - 5I - 6I + 21 &= 0, \\ -21I + 42 &= 0, \\ 42 &= 21I, \\ I &= 2 \text{ amperes.} \end{aligned}$$

I is positive and therefore the assumed direction of current flow is correct. (In this case the direction of current flow was obvious.)

The total power absorbed by the resistors in figure 4-2 (A), is the sum of the power absorbed by each resistor.

The power in $R1$ is $I^2R_1 = 2^2 \times 1 = 4$ watts.
The power in $R2$ is $I^2R_2 = 2^2 \times 2 = 8$ watts.
The power in $R3$ is $I^2R_3 = 2^2 \times 3 = 12$ watts.
The power in $R4$ is $I^2R_4 = 2^2 \times 4 = 16$ watts.
The power in $R5$ is $I^2R_5 = 2^2 \times 5 = 20$ watts.
The power in $R6$ is $I^2R_6 = 2^2 \times 6 = 24$ watts.

Note that in the above calculations for power the current values in each is the same because these calculations apply to a series circuit. The total power absorbed is

$$4 + 8 + 12 + 16 + 20 + 24 = 84 \text{ watts.}$$

A check on the calculation is that the total power absorbed is equal to I_tE_t, or

$$2 \times (21 + 21) = 84 \text{ watts.}$$

In figure 4-2 (B), the voltage sources are bucking. Because E_{s2} is larger then E_{s1}, E_s2 determines the direction of current flow, and this direction is clockwise around the circuit. Starting at the left terminal of $R1$ and proceeding clockwise around the circuit, the voltage equation is,

$$- E_1 - E_2 + E_{s2} - E_3 - E_4 - E_5 - E_6 - E_{s1} = 0,$$

or

$$- I - 2I + 92 - 3I - 4I - 5I - 6I - 29 = 0,$$

from which

$$I = \frac{92 - 29}{21} = 3 \text{ amperes.}$$

The power absorbed by $R1$ is $I^2R_1 = 3^2$ x 1 = 9 watts.
The power absorbed by $R2$ is $I^2R_2 = 3^2$ x 2 = 18 watts.
The power absorbed by $R3$ is $I^2R_3 = 3^2$ x 3 = 27 watts.
The power absorbed by $R4$ is $I^2R_4 = 3^2$ x 4 = 36 watts.
The power absorbed by $R5$ is $I^2R_5 = 3^2$ x 5 = 45 watts.
The power absorbed by $R6$ is $I^2R_6 = 3^2$ x 6 = 54 watts.
The total power is

$$9 + 18 + 27 + 36 + 45 + 54 = 189 \text{ watts.}$$

A check on the calculation is that the total power absorbed is equal to the product of the net voltage, acting in the direction of electron flow, and the current, or

$$EI = (92 - 29) \times 3 = 189 \text{ watts.}$$

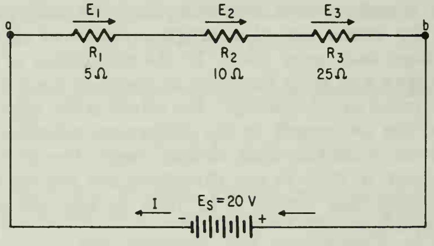
TYPICAL PROBLEMS IN SERIES CIRCUITS

As seen by the preceding calculations, problems involving the determination of resistance, voltage, current, and power in a series circuit are relatively simple. It is necessary only to draw or visualize the circuit, to list the known values, and to determine by means of Ohm's Law (or Kirchhoff's adaptation of Ohm's Law) the unknown values.

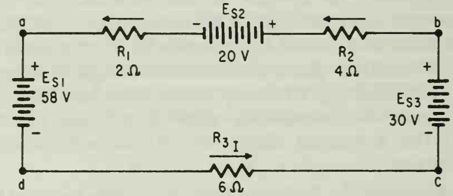
In figure 4-3 (A), it is desired to find the total resistance, R_t, the current, I, and the voltage drops across $R1$, $R2$, and $R3$.

The total resistance is equal to the sum of the individual resistors. Thus,

$$R_t = R_1 + R_2 + R_3 = 5 + 10 + 25 = 40\Omega.$$



VOLTAGE AROUND SERIES CIRCUIT HAVING ONE VOLTAGE SOURCE
(A)



VOLTAGES AROUND SERIES CIRCUIT HAVING VOLTAGE SOURCES IN OPPOSITION
(B)

Figure 4-3.—Solving for R_t, E, and I in series circuits.

The current is

$$I = \frac{E_s}{R_t} = \frac{20}{40} = 0.5 \text{ ampere.}$$

The current is the same in all parts of the series circuit, and therefore the same current flows through $R1$, $R2$, and $R3$. The voltage drops across $R1$, $R2$, and $R3$ are indicated as

$$E_1 = I \times R_1 = 0.5 \times 5 = 2.5 \text{ volts,}$$

$$E_2 = I \times R_2 = 0.5 \times 10 = 5 \text{ volts,}$$

and

$$E_3 = I \times R_3 = 0.5 \times 25 = 12.5 \text{ volts.}$$

According to Kirchhoff's Voltage Law, the sum of the individual voltage drops is equal to the source voltage, or

$$E_s = E_1 + E_2 + E_3 = 2.5 + 5 + 12.5 = 20 \text{ volts.}$$

The power absorbed by $R1$ is $\frac{E_1{}^2}{R_1} = \frac{(2.5)^2}{5} =$ 1.25 watts.

The power absorbed by $R2$ is $\frac{E_2{}^2}{R_2} = \frac{5^2}{10} =$ 2.50 watts.

The power absorbed by $R3$ is $\frac{E_3{}^2}{R_3} = \frac{(12.5)^2}{25} =$ 6.25 watts.

The total power absorbed by the 3 resistors is 1.25 + 2.5 + 6.25, or 10 watts. This value may be checked by the equation,

$$P_t = E_t I_t = 20 \times 0.5 = 10 \text{ watts.}$$

In the example of figure 4-3 (B), the circuit trace is arbitrarily started at point *a* and continued in a clockwise direction completely around the circuit and back to point *a*. The voltage equation is written in terms of both (1) known voltages and (2) current and resistance. The equation is solved for current in terms of voltage and resistance. The three voltage sources are arranged so that E_{s1} and E_{s2} are additive and both are opposed to E_{s3}. Since the sum of E_{s1} and E_{s2} is greater than E_{s3} the electron flow is determined by E_{s1} and E_{s2} and is seen to be in a counterclockwise direction around the circuit as indicated by the arrows above the resistors.

Representing the unknown current as I, the voltage equation is,

$$2I - 20 + 4I + 30 + 6I - 58 = 0$$

$$12I - 48 = 0$$

$$I = \frac{48}{12} = 4 \text{ amperes.}$$

The voltage drop across $R1$ is $IR_1 = 4 \times 2 =$ 8 volts.

The voltage drop across $R2$ is $IR_2 = 4 \times 4 =$ 16 volts.

The voltage drop across $R3$ is $IR_3 = 4 \times 6 =$ 24 volts.

The total voltage acting in the direction of electron flow is equal to

$$8 + 16 + 24, \text{ or } 48 \text{ volts.}$$

The power absorbed in $R1$ is $I^2R_1 = 4^2 \times 2 =$ 32 watts.

The power absorbed in $R2$ is $I^2R_2 = 4^2 \times 4 =$ 64 watts.

The power absorbed in $R3$ is $I^2R_3 = 4^2 \times 6 =$ 96 watts.

The total power absorbed by the three resistors is

$$32 + 64 + 96 = 192 \text{ watts.}$$

The calculation may be checked by the relation

$$P_t = E_t I = 48 \times 4 = 192 \text{ watts.}$$

The filaments of light bulbs and electron tubes are made of materials that have appreciable resistance. Most incandescent lamps have tungsten filaments. The heat produced by the current flowing through the resistance of the filament is intense enough to make the tungsten wires white hot and thus produce artificial light. Radio receivers of the common a-c/d-c variety have their filaments connected in series, as shown in figure 4-4. The tube designations are shown directly above the filament symbols, $R1$, $R2$, and so forth. The first two numerals in the designation indicate the approximate voltage that must be applied to the filament to cause rated current to flow. For example, 12 volts must be applied to the filament of the 12SA7 tube to cause the rated current of 0.15 ampere to flow.

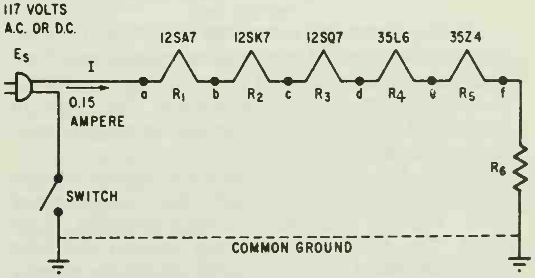


Figure 4-4.—Typical series circuit.

The first problem is to find the value of $R6$ that will cause 0.15 ampere to flow in the circuit when the applied voltage is 117 volts. By observation it is seen that the tube filaments will absorb

$$12 + 12 + 12 + 35 + 35 = 106 \text{ volts.}$$

Therefore, $R6$ must absorb the difference, or

$$117 - 106 = 11 \text{ volts.}$$

The resistance of $R6$ is,

$$R6 = \frac{E_6}{I} = \frac{11}{0.15} = 73.3 \text{ ohms.}$$

The power, P_6, absorbed by $R6$ is

$$P_6 = E_6 \times I = 11 \times 0.15 = 1.65 \text{ watts.}$$

The power absorbed by the 12SA7 filament is

$$P_1 = E_1 I = 12 \times 0.15 = 1.8 \text{ watts.}$$

The power absorbed by the 12SK7 and the 12SQ7 filaments is also 1.8 watts each, since they both have equal voltages and the same value of current. The 35L6 filament absorbs an amount of power equal to 35 x 0.15 = 5.25 watts and the 35Z4 filament absorbs an equal amount of power. The total power absorbed by the entire filament circuit is equal to the sum of the power absorbed by each separate unit. Thus,

$$P_t = 1.8 + 1.8 + 1.8 + 5.25 + 5.25 + 1.65 = 17.55 \text{ watts.}$$

The total power may be checked as follows:

$$P_t = E_t I = 117 \times 0.15 = 17.55 \text{ watts.}$$

In the foregoing examples of series circuits, an important relation should be pointed out. Note that the voltage dropped across each resistor is in proportion to its resistance. This fact is important and should be thoroughly understood. It is explained as follows:

When the power switch in a series circuit is closed, current through the circuit rises very rapidly. As the current increases from zero, the total voltage drop across the load also increases until it exactly equals the source voltage, at which time the current stabilizes at a steady flow. In this natural state of balance, the voltage absorbed by each ohm of resistance will depend on two things, (1) how many source volts must be absorbed, and (2) how many ohms there are in the circuit to absorb them. The voltage that each ohm of resistance must absorb is determined by dividing the total voltage by the total number of ohms. Thereafter, when the circuit is closed, current will rise until each ohm of resistance is absorbing, or dropping, a voltage that is maximum in value, and equal to all the others. Current will stabilize when the sum of all the ohmic drops equals the source, or impressed voltage. This is Kirchhoff's Voltage Law in action. Because the voltage-per-ohm and the series current vary directly and simultaneously, they must therefore be equal. For instance, when there are 10 amperes of current through one ohm of resistance, the voltage absorbed by that one ohm is 10 volts. Thus, the division of total voltage by the total number of ohms yields TWO values, (1) the voltage absorbed per ohm, and (2) the total current.

The Ohm's Law Formula $\frac{E}{R} = I$ is most often used to express this relation. It could also be written $\frac{E}{R} = e$, where e is the volts-per-ohm value for a series circuit, because e and I are interchangeable. The voltage absorbed by any particular resistor is equal to the voltage-per-ohm value for the circuit, multiplied by the number of ohms in the particular resistor. This relation could thus be written $E = eR$. In practice, however, I is most often substituted for e, and the relation becomes $E = IR$. Hence, the commonly-used term "IR drop."

The voltages around the series circuit shown in figure 4-4 are distributed in proportion to the resistances around the circuit. Thus, the voltage between any point, for example, ground, and some other point such as a, b, or c may be determined. For example, the potential from a to ground is the full 117 volts because the entire circuit is included. From b to ground, the potential is 117 volts less the drop of 12 volts across $R1$, or 105 volts, because the circuit includes everything except $R1$. The potential between point f and ground is 11 volts because $R6$ alone is included in this part of the circuit.

In this type of circuit, when an open occurs in any of the filaments or in $R6$, the current ceases to flow. However, the input current increases if any of the points, a, b, c, and so forth, should become grounded. For example, if point f should become grounded the resistance of $R6$ is no longer in the circuit, and 117 volts is applied between points a and f instead of 106 volts. The total filament current is increased to

$$\frac{117}{106} \times 0.15 = 0.165 \text{ ampere.}$$

The increase in current is proportioned to the increase in voltage. Over-voltage may cause the filament to overheat because of excessive current. Thus, the entire filament circuit will be deenergized when the circuit opens at some point due to filament burnout.

Effect of Source Resistance on Voltage, Power, and Efficiency

All sources of e.m.f. have some internal resistance that acts in series with the load resistance. The source resistance is generally indicated in circuit diagrams as a separate resistor connected in series with the source. Both the voltage and power made available to the load may be increased if the resistance of the source is reduced.

The effects of source resistance, R_S, on load voltage may be illustrated by the use of figure 4-5. In figure 4-5 (A), the circuit is open, and therefore a voltmeter connected across the battery will read the open-circuit voltage. In the case of a dry cell, the open-circuit voltage is 1.5 volts. In figure 4-5 (B), the cell is short-circuited through the ammeter, and a current of 30 amperes flows from the source. In this case the voltage of the cell is developed across the internal resistance of the cell. The internal resistance of the cell is therefore,

$$R_s = \frac{E_s}{I} = \frac{1.5}{30} = 0.05 \text{ ohm.}$$

If a load, R_L, of 0.10 ohm is connected to the circuit, as shown in figure 4-5 (C), the current, I, becomes

$$I = \frac{E_s}{R_t} = \frac{1.5}{0.15} = 10 \text{ amperes.}$$

The voltage available at the load is

$$E_L = IR_L = 10 \times 0.1 = 1 \text{ volt.}$$

The voltage absorbed across the internal resistance of the cell is

$$IR_s = 10 \times 0.05 = 0.5 \text{ volt.}$$

Thus the effect of the internal resistance is to decrease the terminal voltage from 1.5 volts to 1 volt when the cell delivers 10 amperes to the load.

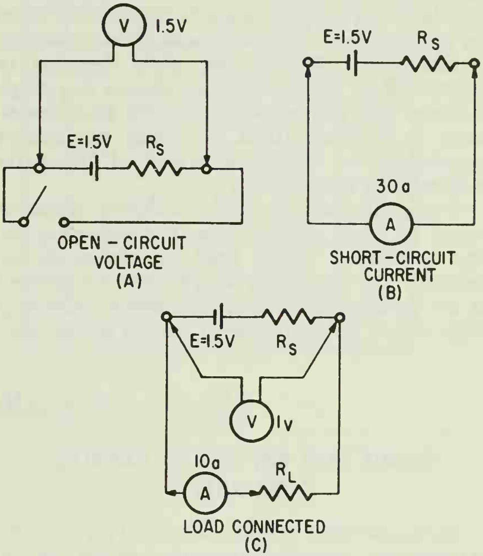


Figure 4-5.—Effect of source resistance on load voltage.

The effect of the source resistance on the power output of a d-c source may be shown by an analysis of the circuit in figure 4-6 (A). When the variable load-resistor, R_L, is set at the zero ohms position (equivalent to a short circuit) the current is limited only by the internal resistance, R_S, of the source. The short-circuit current, I, is determined as

$$I = \frac{E_s}{R_s} = \frac{100}{5} = 20 \text{ amperes.}$$

This is the maximum current that may be drawn from the source. The terminal voltage across the short circuit is zero and all the voltage is absorbed within the terminal resistance of the source.

If the load resistance, R_L, is increased (the internal resistance remaining the same), the current drawn from the source will decrease. Consequently, the voltage drop across the internal resistance will decrease. At the same time, the terminal voltage applied across the load will increase and will approach a maximum as the current approaches zero.

The MAXIMUM POWER TRANSFER THEOREM says in effect that maximum power is transferred from the source to the load when the resistance of the load is equal to the internal resistance of the source. This theorem is illustrated in the tabular chart and the graph of figure 4-6 (B) and (C). When the load resistance is 5 ohms, thus matching the source resistance, the maximum power of 500 watts is developed in the load.

The efficiency of power transfer (ratio of output to input power) from the source to the load increases as the load resistance is increased. The efficiency approaches 100 percent as the load resistance approaches a relatively large value compared with that of the source, since less power is lost in the source. The efficiency of power transfer is only 50 percent at the maximum power transfer resistance of 5 ohms and approaches zero efficiency at relatively low values of load resistance compared with that of the source.

Thus the problem of high efficiency and maximum power transfer is resolved as a compromise somewhere between the low efficiency of maximum power transfer and the high efficiency of the high-resistance load. Where the amounts of power involved are large and the efficiency is important, the load resistance is made large relative to the source resistance so that the losses are kept small. In this case the efficiency will be high. Where the problem of matching a source to a load is of paramount importance, as in communications circuits, a strong signal may be more important than a high percentage of efficiency. In such cases, the efficiency of transmission will be only about 50 percent. However, the power of transmission will be the maximum of which the source is capable of supplying.

Parallel Circuits

OHM'S LAW APPLIED TO PARALLEL CIRCUITS

In the parallel circuit, each load (or branch), is connected directly across the voltage source, as shown in figure 4-7. As a result, there are as many separate paths for current flow as there are branches. When additional loads were added in the series circuit, total resistance was increased and total current decreased. In the parallel circuit, just the opposite is true. As loads are added in parallel, they simply become additional paths for current flow, and therefore the total current supplied by the source increases as they are added. If total current is increased, total resistance must have been decreased. Therefore, as branches are added in parallel, regardless of their resistances, the total resistance as seen from the voltage source DECREASES.

The voltage across all branches of a parallel circuit is the same, because all branches are connected directly to the voltage source. Consequently, the current through each branch is independent of the others, and depends only on the resistance of the particular branch, at a given voltage. The current through each branch may thus be computed separately, simply by dividing its resistance into the source voltage. The branch currents in figure 4-7 are:

$$I_1 = \frac{E_s}{R_1} = \frac{30}{5} = 6 \text{ amperes,}$$

$$I_2 = \frac{E_s}{R_2} = \frac{30}{10} = 3 \text{ amperes,}$$

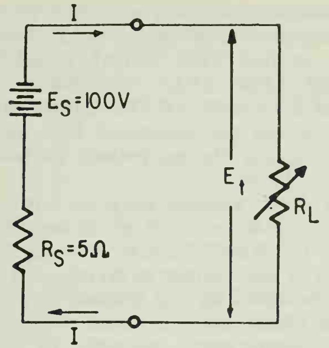
and

$$I_3 = \frac{E_s}{R_3} = \frac{30}{30} = 1 \text{ ampere.}$$

The total current, I_t, of the parallel circuit is equal to the sum of the currents through the individual branches. This, in slightly different words, is Kirchhoff's current law, which is treated later in this chapter. In this case, the total current is

$$I_t = I_1 + I_2 + I_3 = 6 + 3 + 1 = 10 \text{ amperes.}$$

In order to find the equivalent, or total resistance, R_t (for simplicity, R_t is used instead of R_{eq}), of the combination shown in figure 4-7, Ohm's law is first used to find each of the

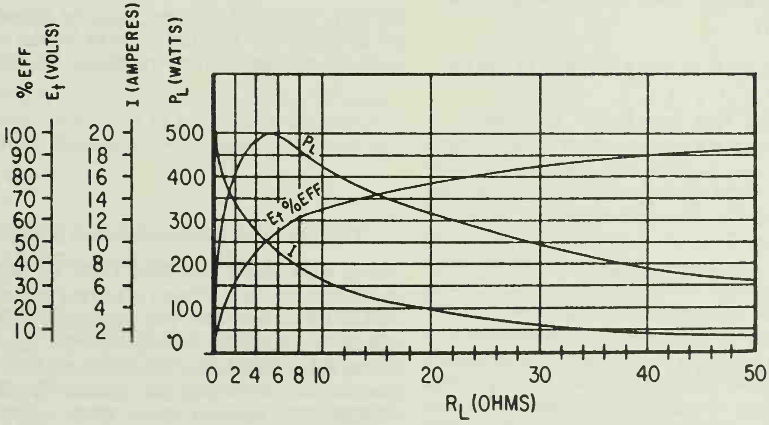


E_S= OPEN-CIRCUIT VOLTAGE OF SOURCE
R_S=INTERNAL RESISTANCE OF SOURCE
E_t =TERMINAL VOLTAGE
R_L=RESISTANCE OF LOAD
P_L =POWER USED IN LOAD
I =CURRENT FROM SOURCE
% EFF. = PERCENTAGE OF EFFICIENCY

(A)
CIRCUIT AND SYMBOL DESIGNATIONS

R_L	E_t	I	P_L	%EFF.
0	0	20	0	0
1	16.6	16.6	267.6	16.6
2	28.6	14.3	409	28.6
3	37.5	12.5	468.8	37.5
4	44.4	11.1	492.8	44.4
5	50	10	500	50
6	54.5	9.1	495.4	54.5
7	58.1	8.3	482.2	58.1
8	61.6	7.7	474.3	61.6
9	63.9	7.1	453.7	63.9
10	66	6.6	435.6	66
20	80	4	320	80
30	87	2.9	252	87
40	88	2.2	193.6	88
50	91	1.82	165	91

(B)
CHART



(C)
GRAPH

Figure 4-6.—Effect of source resistance on power output.

currents (I_t, I_1, I_2, and I_3). Substituting the Ohm's Law equivalent for current ($\frac{E}{R}$) in the current equation, that equation ($I_t = I_1 + I_2 + I_3$) becomes

$$\frac{E_s}{R_t} = \frac{E_s}{R_1} + \frac{E_s}{R_2} + \frac{E_s}{R_3}$$

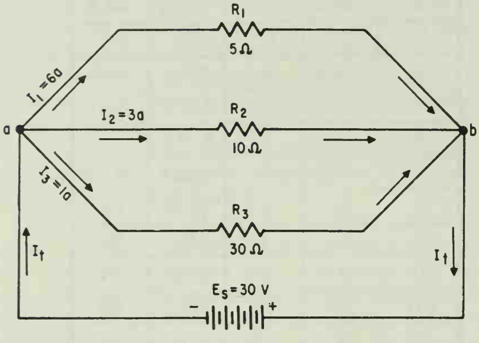


Figure 4-7.—Resistors in parallel.

This introduces the factor R_t into the equation, which is the quantity you are attempting to determine. Since E_s appears as the numerator in all four factors, it is divided out, and the equation then contains only the desired factor R_t:

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3},$$

$$= \frac{1}{5} + \frac{1}{10} + \frac{1}{30},$$

$$= 0.2 + 0.1 + 0.033,$$

$$\frac{1}{R_t} = 0.333,$$

$$R_t = \frac{1}{0.333},$$

$$= 3 \text{ ohms (approx.).}$$

A useful rule to remember in computing the equivalent resistance of a d-c parallel circuit is that THE TOTAL RESISTANCE IS ALWAYS LESS THAN THE SMALLEST RESISTANCE IN ANY OF THE BRANCHES.

There are two shortcuts that may be used in solving for the equivalent resistance of a parallel circuit.

The first applies only to any number of parallel resistors all of which have THE SAME VALUE OF RESISTANCE. The equivalent resistance is determined by dividing the resistance of one resistor by the number of resistors in parallel. Thus, the equivalent resistance of five 10-ohm resistors connected in parallel is

$$R_t = \frac{10}{5} = 2 \text{ ohms.}$$

The second shortcut applies when two and only two resistors of different values are connected in parallel. The equivalent resistance is equal to their product divided by their sum. For example, if two resistors having resistances of 3 ohms and 6 ohms are connected in parallel, the equivalent resistance is

$$R_t = \frac{R_1 R_2}{R_1 + R_2} = \frac{3 \times 6}{3 + 6} = \frac{18}{9} = 2 \text{ ohms.}$$

In addition to adding the individual branch currents to obtain the total current in a parallel circuit, the total current may be found directly by dividing the applied voltage by the equivalent resistance, R_t. For example, in figure 4-7

$$I_t = \frac{E_s}{R_t} = \frac{30}{3} = 10 \text{ amperes.}$$

The quantity $\frac{1}{R}$, as used in the foregoing equations, expresses CONDUCTANCE, whose standard symbol is G. When referring to the RESISTANCE of a circuit, you visualize the degree to which it RESISTS or PREVENTS current flow. When referring to its conductance, you visualize the degree to which the circuit PERMITS or CONDUCTS current flow. It is well to be able to work from either standpoint because some problems are easier to solve using circuit conductance instead of resistance, and vice versa.

The total conductance of a circuit is the reciprocal of its total resistance (the reciprocal of any quantity is that quantity divideed into one). Thus, the total conductance of a circuit is written

$$G_t = \frac{1}{R_t}$$

and

$$R_t = \frac{1}{G_t}$$

The term RELATIVE CONDUCTANCE applies to the comparison of two or more parallel branches. When two or more resistors are connected in parallel, each will conduct current in proportion to its resistance. To compare their relative conductances, each resistance is divided into the common numerator, 1. The larger a resistance the smaller its current flow, or relative conductance. The total conductance is the simple sum of all branch conductances:

$$G_t = G_1 + G_2 + G_3 + \cdots\cdots$$

or

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots\cdots$$

Since G and R are each an inversion of the other, as shown in equation (fig. 4-1), it follows that their Ohm's-Law equivalents are also inverted. That is, where R is expressed as $\frac{E}{I}$, G is expressed as $\frac{I}{E}$. Wherever R is used in Ohm's Law equations, the reciprocal of G may be used. For instance, where R is used as a multiplier in expressing E, ($E = IR$), G would be used as a divisor, ($E = \frac{I}{G}$).

KIRCHHOFF'S CURRENT LAW APPLIED TO PARALLEL CIRCUITS

Kirchhoff's current law states that AT ANY JUNCTION OF CONDUCTORS THE ALGEBRAIC SUM OF THE CURRENTS IS ZERO. This is another way of saying that as many electrons must leave a junction as enter it. Consider junction a of figure 4-7. Assume that the current flowing toward junction a is positive and that the currents flowing away from the junction—that is, currents I_1, I_2, and I_3—are negative. Kirchhoff's current law is then expressed mathematically as

$$+I_t - I_1 - I_2 - I_3 = 0,$$

or

$$10 - 6 - 3 - 1 = 0.$$

As in the series circuit, the total power consumed in a parallel circuit is equal to the sum of the power consumed in the individual resistors. The power P_1, consumed in $R1$ of figure 4-7 is

$$P_1 = EI_1 = 30 \times 6 = 180 \text{ watts;}$$

the power, P_2, consumed in $R2$ is

$$P_2 = EI_2 = 30 \times 3 = 90 \text{ watts;}$$

and the power P_3, consumed in $R3$ is

$$P_3 = EI_3 = 30 \times 1 = 30 \text{ watts.}$$

The total power, P_t, consumed is the sum of the power consumed in the individual branch units—that is,

$$P_t = P_1 + P_2 + P_3 = 180 + 90 + 30 = 300 \text{ watts.}$$

The total power may be checked as

$$P_t = EI_t = 30 \times 10 = 300 \text{ watts.}$$

TYPICAL PROBLEMS IN PARALLEL CIRCUITS

Problems involving the determination of resistance, voltage, current, and power in a parallel circuit are solved as simply as in a series circuit. The procedure is the same—(1) draw a circuit diagram, (2) state the values given and the values to be found, (3) state the applicable equations, and (4) substitute the given values and solve for the unknown.

For example, the parallel circuit of figure 4-8 consists of 2 branches (a and b). Branch a consists of 3 lamps in parallel. Their ratings are L_1 = 50 watts, L_2 = 25 watts, and L_3 = 75 watts. Branch b also has 3 lamps in parallel with ratings of L_4 = 150 watts, L_5 = 200 watts, and L_6 = 250 watts. The source voltage is 100 volts.

1. Find the current in each lamp.
2. Find the resistance of each lamp.
3. Find the current in branch a.

4. Find the current in branch *b*.
5. Find the total circuit current.
6. Find the total circuit resistance.
7. Find the total power supplied to the circuit.
8. Check 7 by a separate calculation.

1. The current in $L1$ is $I = \frac{P}{E} = \frac{50}{100} = 0.50$ ampere.

   The current in $L2$ is $\frac{25}{100} = 0.25$ ampere.

   The current in $L3$ is $\frac{75}{100} = 0.75$ ampere.

   The current in $L4$ is $\frac{150}{100} = 1.50$ amperes.

   The current in $L5$ is $\frac{200}{100} = 2.00$ amperes.

   The current in $L6$ is $\frac{250}{100} = 2.5$ amperes.

2. The resistance of $L1$ is $R = \frac{E}{I} = \frac{100}{0.5} = 200$ ohms.

   The resistance of $L2$ is $\frac{100}{0.25} = 400$ ohms.

   The resistance of $L3$ is $\frac{100}{0.75} = 133$ ohms.

   The resistance of $L4$ is $\frac{100}{1.5} = 66.7$ ohms.

   The resistance of $L5$ is $\frac{100}{2.0} = 50$ ohms.

   The resistance of $L6$ is $\frac{100}{2.5} = 40$ ohms.

3. The current in branch *a* is

$$I_1 + I_2 + I_3 = 0.5 + 0.25 + 0.75 = 1.5 \text{ amperes.}$$

4. The current in branch *b* is

$$I_4 + I_5 + I_6 = 1.5 + 2.0 + 2.5 = 6.0 \text{ amperes.}$$

5. The total circuit current is

$$I_a + I_b = 1.5 + 6.0 = 7.5 \text{ amperes.}$$

6. The total circuit resistance is

$$R_t = \frac{E}{I_t} = \frac{100}{7.5} = 13.3 \text{ ohms.}$$

7. The total power supplied to the circuit is

$$50 \text{ w.} + 25 \text{ w.} + 75 \text{ w.} + 150 \text{ w.} + 200 \text{ w.} + 250 \text{ w.} = 750 \text{ watts.}$$

8. The total power is also equal to

$$P_t = EI_t = 100 \times 7.5 = 750 \text{ watts.}$$

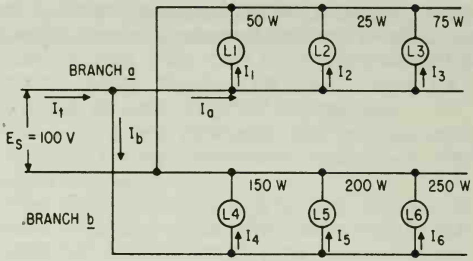


Figure 4-8.—Typical parallel circuit.

PRACTICAL APPLICATIONS OF SERIES AND PARALLEL CIRCUITS

One of the most common series circuits is the familiar string of Christmas tree lamps. When one of the lamps in the string burns out, all of the lamps go out because there is no longer a complete pathway through which the electrons can flow.

If the string is composed of 10 lamps of the same power rating and it is connected to a 120-volt source, 12 volts will be applied across each lamp. If one of the lamps burns out and the line is then shorted across the socket of the burned-out lamp, current will continue to flow through the remaining 9 lamps. However, the source voltage of 120 volts will be applied to the remaining lamps, and 13.3 volts will be developed across each lamp. The resultant increase in current flow may quickly burn out another lamp in the string.

Airport runway lamps and street lamps are other applications of series circuits. For these applications, constant-current variable-voltage sources are employed. Where long circuits like these are used, line losses are kept to a minimum by the use of high voltage and low current. When one of the lamps burns out, a device at the lamp automatically shorts out the defective lamp, thus allowing the others to continue to burn. At the variable-voltage source there is an automatic reduction in voltage when the current tends to increase so that the rise in current through the remaining lamps is checked and the circuit current remains approximately constant at the rated value.

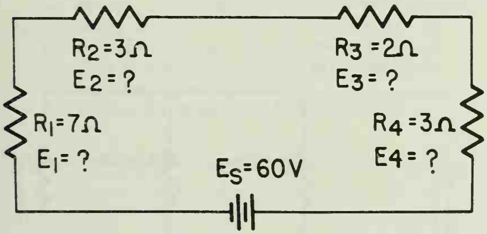
Most power and light distribution circuits are basically parallel circuits supplied by constant-potential variable-current sources.

Ship's service distribution systems are typical parallel circuits where many branch circuits are connected in parallel across the bus bars (the massive conductors that tie to the source).

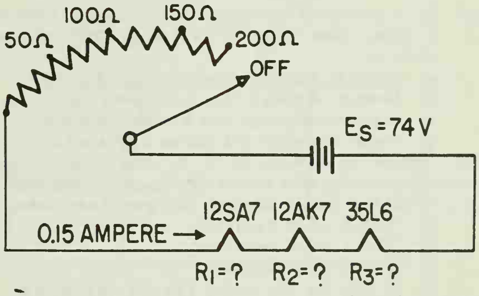
Distribution systems used in homes and factories are essentially networks of parallel circuits. The service conductors (the wires that bring the current to the home) are connected to the branch parallel circuits via a service switch and fuses. Each parallel circuit that is connected to the main circuit is likewise supplied with a fuse or circuit breaker of a lower current rating. On each individual branch circuit lamps or other loads are connected in parallel. Thus, in the home there are branch parallel circuits in parallel with other branch parallel circuits. Actually, nearly all the commonly encountered distribution electrical circuits are parallel circuits if the line resistance is disregarded.

QUIZ

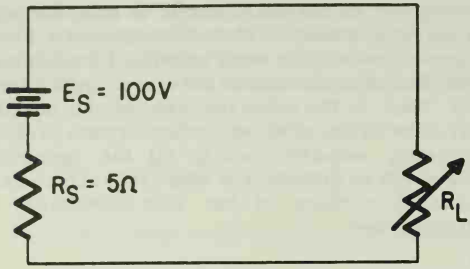
1. If a circuit is constructed so as to allow the electrons to follow only one possible path, the circuit is called a/an
   a. series-parallel circuit
   b. incomplete circuit
   c. series circuit
   d. parallel circuit
2. According to Kirchhoff's Law of Voltages, the algebraic sum of all the votages in a series circuit is equal to
   a. zero
   b. source voltage
   c. total voltage drop
   d. the sum of the IR drop of the circuit
3. In a series circuit, the total current is
   a. always equal to the source voltage
   b. determined by the load only
   c. the same through all parts of the circuit
   d. equal to zero at the positive side of the source
4. The correct voltage equation for the circuit below is
   a. $E_s + E_1 + E_2 + E_3 + E_4 = 0$
   b. $E_s - E_1 - E_2 - E_3 - E_4 = 0$
   c. $E_s = - E_1 - E_2 - E_3 - E_4$
   d. $- E_s = E_1 + E_2 + E_3 + E_4$



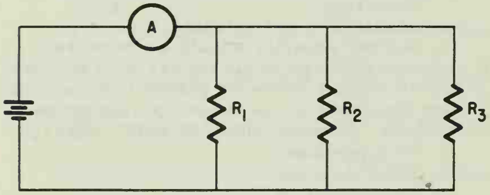
5. (Refer to the circuit used with question 4.) After expressing the voltage drops around the circuit in terms of current and resistance and the given values of source voltage, the equation becomes
   a. $-60 - 7I - 3I - 2I - 3I = 0$
   b. $-60 + 7I + 3I + 2I + 3I = 0$
   c. $60 - 7I - 3I - 2I - 3I = 0$
   d. $60 + 7I + 3I + 2I + 3I = 0$
6. By the use of the correct equation, it is found that the current (I) in the circuit used with question 4 is of positive value. This indicates that the
   a. assumed direction of current flow is correct
   b. assumed direction of current flow is incorrect
   c. problem is not solvable
   d. battery polarity should be reversed
7. In what position would the variable rheostat in the circuit below be placed in order that the filaments of the tubes operate properly with a current flow of 0.15 ampere?
   a. 50 Ω position
   b. 100 Ω position
   c. 150 Ω position
   d. 200 Ω position



8. The power absorbed by the variable rheostat in the circuit used with question 7, when placed in its proper operating position, would be
   a. 112.50 watts
   b. 2.25 watts
   c. 337.50 watts
   d. 450.00 watts
9. In the circuit below, maximum power would be transferred from the source to the load (R_L) if R_L were set at
   a. 2 ohms
   b. 5 ohms
   c. 12 ohms
   d. 24 ohms



10. In the circuit below, if an additional resistor were placed in parallel to R_3 the ammeter reading would
a. increase
b. decrease
c. remain the same
d. drop to zero

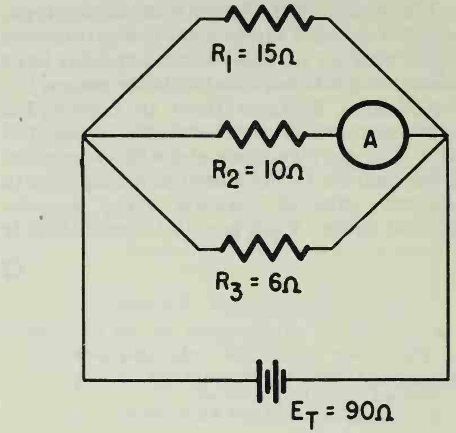


11. In a parallel circuit containing a 4-ohm, 5-ohm, and 6-ohm resistor, the current flow is
a. highest through the 4-ohm resistor
b. lowest through the 4-ohm resistor
c. highest through the 6-ohm resistor
d. equal through all three resistors

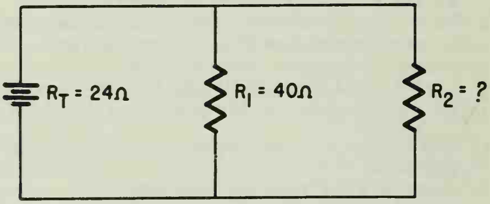
12. Three resistors of 2, 4, and 6 ohms, respectively, are connected in parallel. Which resistor would absorb the greatest power?
a. The 2-ohm resistor
b. The 4-ohm resistor
c. The 6-ohm resistor
d. It will be the same for all resistors

13. If three lamps are connected in parallel with a power source, connecting a fourth lamp in parallel will
a. decrease E_T
b. decrease I_T
c. increase E_T
d. increase I_T

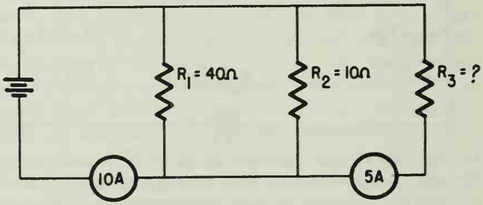
14. What is the current flow through the ammeter in the circuit shown below?
a. 4 amps
b. 9 amps
c. 15 amps
d. 28 amps



15. In the circuit shown below, the total resistance is 24 ohms. What is the value of R_2?
a. 16 ohms
b. 40 ohms
c. 60 ohms
d. 64 ohms

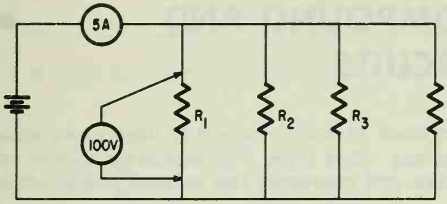


16. What is the source voltage of the circuit shown below?
a. 40 volts
b. 50 volts
c. 100 volts
d. 500 volts

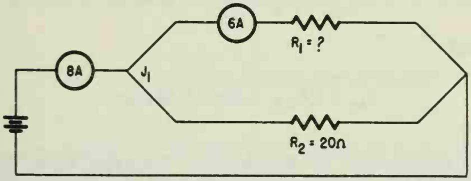


17. What is the value of R_3 in the circuit used with question 16?
a. 8 ohms
b. 10 ohms
c. 20 ohms
d. 100 ohms

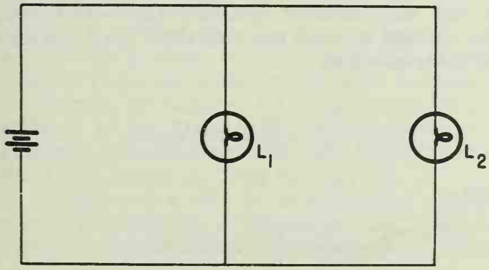
18. If all 4 resistors in the circuit below are of equal ohmic resistances, what is the value of R_3?
    a. 5 ohms
    b. 20 ohms
    c. 60 ohms
    d. 80 ohms



19. What is the value of the source voltage in the circuit below?
    a. 20 volts
    b. 40 volts
    c. 120 volts
    d. 160 volts

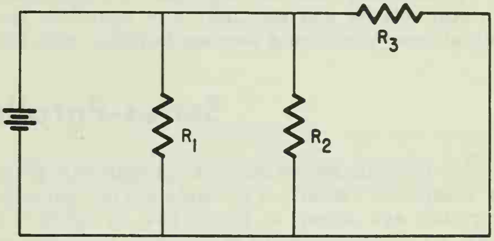


20. If lamp L_2 in the circuit below should suddenly burn out, which of the below statements is correct?
    a. More current would flow through lamp L_1
    b. Source voltage would decrease
    c. The filament resistance of lamp L_1 would decrease
    d. Lamp L_1 would still burn normal

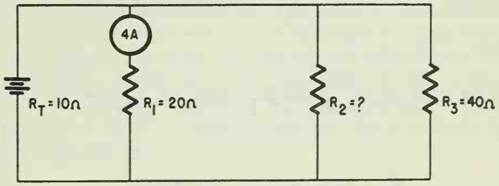


21. When referring to a circuit's conductance, you visualize the degree to which the circuit
    a. permits or conducts voltage
    b. opposes the rate of voltage changes
    c. permits or conducts current flow
    d. opposes the rate of current flow

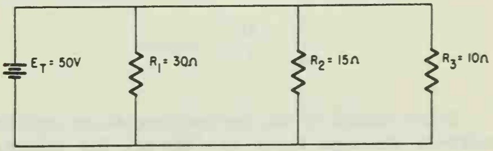
22. The total conductance of the circuit below would be solved by which of the equations?
    a. $G_T - G_1 - G_2 - G_3 = 0$
    b. $G_T + G_1 + G_2 + G_3 = 0$
    c. $G_T = G_1 - G_2 - G_3$
    d. $G_T = G_1 + G_2 + G_3$



23. If the resistors in the circuit below are all rated at 250 watts, which resistor or resistors would overheat?
    a. R_1
    b. R_2
    c. R_3
    d. All



24. The total conductance of the circuit below is
    a. 0.15 G
    b. 0.20 G
    c. 0.50 G
    d. 0.75 G



CHAPTER 5

DIRECT-CURRENT COMPOUND AND BRIDGE CIRCUITS

In the compound circuit, loads are connected in both series and parallel. For practical applications, you should become familiar with the compound circuit, since it is used more widely than any other type. You should be able to recognize and segregate the various combinations.

Series-Parallel Combinations

At least three resistors are required to form a compound circuit. Two basic series-parallel circuits are shown in figure 5-1. In figure 5-1 (A), $R1$ is connected in series with the parallel combination made up of $R2$ and $R3$.

The total resistance, R_t, of figure 5-1 (A), is determined in two steps. First, the resistance, $R_{2,3}$, of the parallel combination of $R2$ and $R3$ is determined as

$$R_{2,3} = \frac{R_2 R_3}{R_2 + R_3} = \frac{3 \times 6}{3 + 6} = \frac{18}{9} = 2 \text{ ohms.}$$

The sum of $R_{2,3}$ and R_1—that is, R_t—is

$$R_t = R_{2,3} + R_1 = 2 + 2 = 4 \text{ ohms.}$$

If the total resistance, R_t, and the source voltage, E_s, are known, the total current, I_t, may be determined by Ohm's law. Thus, in figure 5-1 (A),

$$I_t = \frac{E_s}{R_t} = \frac{20}{4} = 5 \text{ amperes.}$$

If the values of the various resistors and the current through them are known, the voltage drops across the resistors may be determined by Ohm's Law. Thus, in figure 5-1 (A),

$$E_{ab} = I_t R_1 = 5 \times 2 = 10 \text{ volts,}$$

and

$$E_{bc} = I_t R_{2,3} = 5 \times 2 = 10 \text{ volts.}$$

According to Kirchhoff's Voltage Law, the sum of the voltage drops around the closed circuit is equal to the source voltage. Thus,

$$E_{ab} + E_{bc} = E_s,$$

or

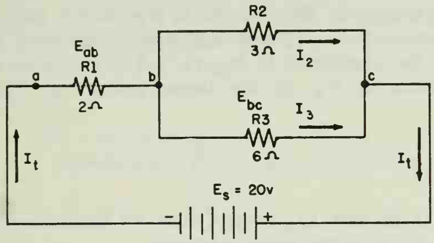
$$10 + 10 = 20 \text{ volts.}$$

If the voltage drop, E_{bc}, across $R_{2,3}$—that is, the drop between points b and c—is known, the current through the individual branches may be determined as

$$I_2 = \frac{E_{bc}}{R_2} = \frac{10}{3} = 3.333 \text{ amperes,}$$

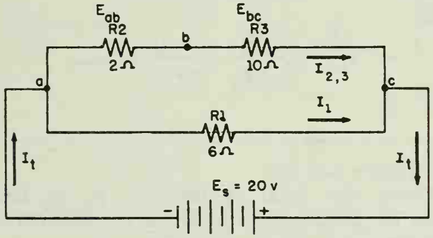
and

$$I_3 = \frac{E_{bc}}{R_3} = \frac{10}{6} = 1.666 \text{ amperes.}$$



R1 IN SERIES WITH PARALLEL COMBINATION OF R2 AND R3

(A)



R1 IN PARALLEL WITH THE SERIES COMBINATION OF R2 & R3

(B)

Figure 5-1.—Compound circuits—series-parallel connections.

According to Kirchhoff's Current Law, the sum of the currents flowing in the individual parallel branches is equal to the total current. Thus,

$$I_2 + I_3 = I_t,$$

or

$$3.333 + 1.666 = 5 \text{ amperes (approx.)}.$$

The total current flows through $R1$; and at point b it divides between the two branches in inverse proportion to the resistance of each branch. Twice as much current goes through $R2$ as through $R3$ because $R2$ has one-half the resistance of $R3$. Thus, 3.333, or two-thirds of 5, amperes flows through $R2$; and 1.666, or one-third of 5, amperes flows through $R3$.

In figure 5-1 (B), $R1$ is in parallel with the series combination of $R2$ and $R3$. The total resistance, R_t, is determined in two steps. First, the sum of the resistance of $R2$ and $R3$—that is, $R_{2,3}$—is determined as

$$R_{2,3} = R_2 + R_3 = 2 + 10 = 12 \text{ ohms.}$$

Second, the total resistance, R_t, is the result of combining $R_{2,3}$ in parallel with $R1$, or

$$R_t = \frac{R_{2,3} R_1}{R_{2,3} + R_1} = \frac{12 \times 6}{12 + 6} = 4 \text{ ohms.}$$

If the total resistance, R_t, and the source voltage, E_s, are known, the total current, I_t may be determined by Ohm's Law. Thus, in figure 5-1 (B),

$$I_t = \frac{E_s}{R_t} = \frac{20}{4} = 5 \text{ amperes.}$$

A portion of the total current flows through the series combination of $R2$ and $R3$ and the remainder flows through $R1$. Because current varies inversely with the resistance, two-thirds of the total current flows through $R1$ and one-third flows through the series combination of $R2$ and $R3$, since R_1 is one-half of $R_2 + R_3$.

The source voltage, E_s, is applied between points a and c, and therefore the current I_1 through $R1$ is

$$I_1 = \frac{E_s}{R_1} = \frac{20}{6} = 3.333 \text{ amperes;}$$

and the current, $I_{2,3}$, through $R_{2,3}$ is

$$I_{2,3} = \frac{E_s}{R_{2,3}} = \frac{20}{12} = 1.666 \text{ amperes.}$$

According to Kirchhoff's Current Law the sum of the individual branch currents is equal to the total current, or

$$I_t = I_1 + I_{2,3},$$

$$5 = 3.333 + 1.667.$$

Compound circuits may be made up of a number of resistors arranged in numerous series and parallel combinations. In more complicated circuits, special theorems, rules, and formulas are used. These are based on Ohm's Law and provide faster solutions for particular applications. Series formulas are applied to the series parts of the circuit, and parallel formulas are applied to the parallel parts. For example, in figure 5-2, the total resistance, R_t, may be obtained in three logical steps.

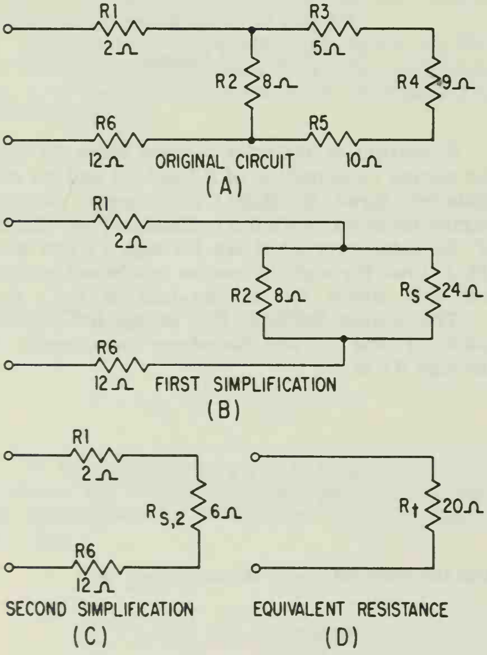


Figure 5-2.—Solving total resistance in a compound circuit.

First, $R3$, $R4$, and $R5$ in figure 5-2 (A), are in series (there is only one path for current) and may be combined in figure 5-2 (B), to give the resistance, R_S, of the three resistors. Thus,

$$R_s = R_3 + R_4 + R_5 = 5 + 9 + 10 = 24 \text{ ohms},$$

and it is now in parallel with $R2$ (because they both receive the same voltage).

The combined resistance of R_S in parallel with $R2$ is

$$R_{s,2} = \frac{R_2 R_s}{R_2 + R_s} = \frac{8 \times 24}{8 + 24} = 6 \text{ ohms},$$

as in figure 5-2 (C).

Third, the total resistance, R_t is determined by combining resistors $R1$ and $R6$ with $R_{S,2}$, as

$$R_t = R_1 + R_6 + R_{s,2} = 2 + 12 + 6 = 20 \text{ ohms}.$$

Other compound circuits may be solved in a similar manner. For example, in figure 5-3, the equivalent resistance, R_t, may be found by simplifying the circuit in successive steps beginning with the resistances, R_1 and R_2. Thus,

$$R_{1,2} = \frac{R_1 R_2}{R_1 + R_2} = \frac{3 \times 6}{3 + 6} = \frac{18}{9} = 2 \text{ ohms},$$

and it is in series with $R3$.

The resistances, $R_{1,2}$ and R_3, are added to give the resultant resistance, $R_{1,2,3}$. Thus,

$$R_{1,2,3} = R_{1,2} + R_3 = 2 + 4 = 6 \text{ ohms}.$$

$R_{1,2,3}$ is in parallel with R_4. The combined resistance, $R_{1,2,3,4}$, is determined as

$$R_{1,2,3,4} = \frac{R_{1,2,3} R_4}{R_{1,2,3} + R_4} = \frac{6 \times 12}{6 + 12} = \frac{72}{18} = 4 \text{ ohms}.$$

This equivalent resistance is in series with $R5$. Thus, the total resistance, R_t, of the circuit is

$$R_t = R_{1,2,3,4} + R_5 = 4 + 8 = 12 \text{ ohms.}$$

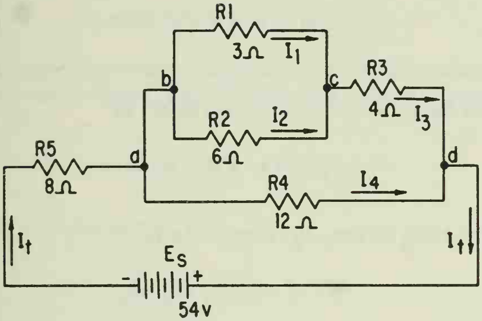


Figure 5-3.—Compound circuit for solving resistance, voltage, current, and power.

By Ohm's Law, the line current, I_t, is

$$I_t = \frac{E_s}{R_t} = \frac{54}{12} = 4.5 \text{ amperes.}$$

The line current flows through $R5$ and therefore the voltage drop, E_5, across $R5$ is

$$E_5 = I_t R_5 = 4.5 \times 8 = 36 \text{ volts.}$$

According to Kirchhoff's Voltage Law, the sum of the voltage drops around the circuit is equal to the source voltage; accordingly, the voltage between points a and d is

$$E_{ad} = E_s - E_5 = 54 - 36 = 18 \text{ volts.}$$

The current through $R4$ is

$$I_4 = \frac{E_4}{R_4} = \frac{18}{12} = 1.5 \text{ amperes.}$$

The resistance, $R_{1,2,3}$, of parallel resistors $R1$ and $R2$ in series with resistor $R3$ is 6 ohms. E_{ad} is applied across 6 ohms; therefore the current, I_3, through R3 is

$$I_3 = \frac{E_{ad}}{R_{1,2,3}} = \frac{18}{6} = 3 \text{ amperes.}$$

The voltage drop, E_3, across $R3$ is

$$E_3 = I_3 R_3 = 3 \times 4 = 12 \text{ volts.}$$

and the voltage across the parallel combination of $R1$ and $R2$—that is, E_{bc}—is

$$E_{bc} = I_{1,2} R_{1,2} = 3 \times 2 = 6 \text{ volts,}$$

where $I_{1,2}$ is the current through the parallel combinations of $R1$ and $R2$. By Kirchhoff's Current Law, $I_{1,2}$ is equal to I_3. The current, I_1 through $R1$ is

$$I_1 = \frac{E_{bc}}{R_1} = \frac{6}{3} = 2 \text{ amperes,}$$

and the current, I_2, through $R2$ is

$$I_2 = \frac{E_{bc}}{R_2} = \frac{6}{6} = 1 \text{ ampere.}$$

The preceding computations may be checked by the application of Kirchhoff's Voltage and Current Law to the entire circuit. Briefly, the sum of the voltage drops around the circuit is equal to the source voltage. Voltage E_5 across $R5$ is 36 volts and voltage E_{ad} across $R4$ is 18 volts—that is,

$$E_s = E_5 + E_{ad},$$

or

$$54 = 36 + 18 \text{ volts.}$$

Likewise, the voltage drop, E_{bc}, across the parallel combination of $R1$ and $R2$ plus the voltage drop, E_3, across $R3$ should be equal to the voltage across points *a* and *d*. E_{bc} is 6 volts and E_3 is 12 volts. Therefore,

$$E_{ad} = E_{bc} + E_3 = 6 + 12 = 18 \text{ volts.}$$

Kirchhoff's Current Law says in effect that the sum of the branch currents is equal to the line current, I_t. The line current is 4.5 amperes, and therefore the sum of I_4 and I_3 should be 4.5 amperes, or

$$I_t = I_4 + I_3 = 1.5 + 3 = 4.5 \text{ amperes.}$$

The power consumed in a circuit element is determined by one of the three power formulas. For example, in figure 5-3 the power, P_1, consumed in $R1$ is

$$P_1 = I_1 E_{bc} = 2 \times 6 = 12 \text{ watts;}$$

the power P_2 consumed in $R2$ is

$$P_2 = I_2 E_{bc} = 1 \times 6 = 6 \text{ watts;}$$

the power P_3 consumed in $R3$ is

$$P_3 = I_3 E_3 = 3 \times 12 = 36 \text{ watts;}$$

the power P_4 consumed in $R4$ is

$$P_4 = I_4 E_4 = 1.5 \times 18 = 27 \text{ watts;}$$

and the power P_5 consumed in $R5$ is

$$P_5 = I_5 E_5 = 4.5 \times 36 = 162 \text{ watts.}$$

The total power, P_t, consumed is

$$\begin{aligned} P_t &= P_1 + P_2 + P_3 + P_4 + P_5 \\ &= 12 + 6 + 36 + 27 + 162 \\ &= 243 \text{ watts.} \end{aligned}$$

The total power is also equal to the total current multiplied by the source voltage, or

$$P_t = I_t E_s = 4.5 \times 54 = 243 \text{ watts.}$$

Voltage Dividers

In practically all electronic devices, such as radio receivers and transmitters, certain design requirements recur again and again. For instance, a typical radio receiver may require a number of different voltages at various points in its circuitry. In addition, all the various voltages must be derived from a single primary power supply. The most common method of meeting these requirements is by the use of a VOLTAGE-DIVIDER network. A typical voltage divider consists of two or more resistors connected in series across the primary power supply. The primary voltage E_s must be as high or higher than any of the individual voltages it is to supply. As the primary voltage is dropped by successive steps through the series resistors, any desired fraction of the original voltage may be "tapped off" to supply individual requirements. The values of the series resistors to be used is dictated by the voltage drops required.

A voltage divider circuit is shown in figure 5-4. The divider is connected across a 270-volt source and supplies three loads simultaneously—10 ma. (one MILLIAMPERE is 0.001 ampere) at 90 volts, between terminal 1 and ground; 5 ma. at 150 volts, between terminal 2 and ground; and 30 ma. at 180 volts, between terminal 3 and ground. The current in resistor *A* is 15 ma. The current, voltage, resistance, and power of the 4 resistors are to be determined.

Kirchhoff's law of currents applied to terminal 1 indicates that the current in resistor *B* is equal to the sum of 15 ma. from resistor *A* and 10 ma. from the 90-volt load. Thus,

$$I_b = 15 + 10, \text{ or } 25 \text{ ma.}$$

Similarly,

$$I_c = 25 + 5 = 30 \text{ ma.},$$

and

$$I_d = 30 + 30 = 60 \text{ ma.}$$

Kirchhoff's Voltage Law indicates that the voltage across resistor *A* is 90 volts; the voltage across *B* is

$$E_b = 150 - 90, \text{ or } 60 \text{ volts;}$$

the voltage across *C* is

$$E_c = 180 - 150, \text{ or } 30 \text{ volts;}$$

and the voltage across *D* is

$$E_d = 270 - 180, \text{ or } 90 \text{ volts.}$$

Before solving for the various resistances it should be recalled that in the formula, $R = \frac{E}{I}$, *R* will be in ohms if *E* is in volts and *I* is in amperes. In many electronic circuits, particularly those being considered, it is just as valid and considerably simpler to let *R* be in thousands of ohms (k-ohms), *E* in volts, and *I* in milliamperes. In the following formulas this convention will be followed.

Applying Ohm's law to determine the resistances—

$$\text{resistance of } A \text{ is } R_a = \frac{E_a}{I_a} = \frac{90}{15} = 6 \text{ k-ohms,}$$

$$\text{resistance of } B \text{ is } R_b = \frac{E_b}{I_b} = \frac{60}{25} = 2.4 \text{ k-ohms,}$$

$$\text{resistance of } C \text{ is } R_c = \frac{E_c}{I_c} = \frac{30}{30} = 1 \text{ k-ohm,}$$

$$\text{resistance of } D \text{ is } R_d = \frac{E_d}{I_d} = \frac{90}{60} = 1.5 \text{ k-ohms.}$$

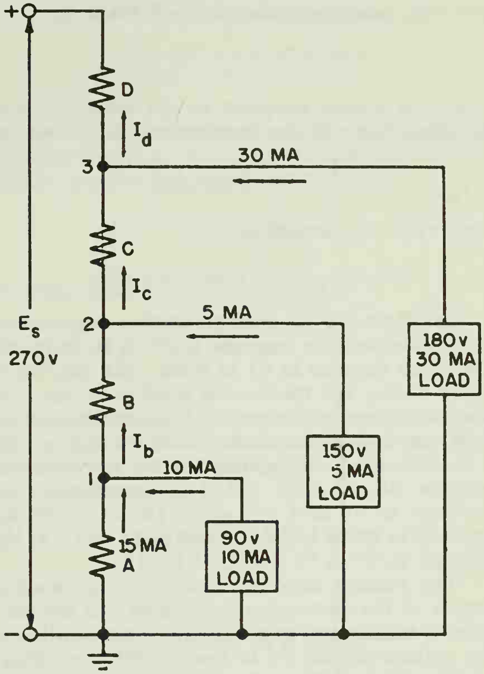


Figure 5-4.—Voltage divider, to determine R and P.

The power absorbed by

$$\text{resistor } A \text{ is } P_a = E_a I_a = 90 \times 0.015 = 1.35 \text{ watts,}$$

$$\text{resistor } B \text{ is } P_b = E_b I_b = 60 \times 0.025 = 1.50 \text{ watts,}$$

$$\text{resistor } C \text{ is } P_c = E_c I_c = 30 \times 0.030 = 0.90 \text{ watts,}$$

$$\text{resistor } D \text{ is } P_d = E_d I_d = 90 \times 0.060 = 5.40 \text{ watts.}$$

The total power absorbed by the 4 resistors is

$$1.35 + 1.50 + 0.90 + 5.40 = 9.15 \text{ watts.}$$

The power absorbed by the load connected to

$$\text{terminal 1 is } P_1 = E_1 I_1 = 90 \times 0.010 = 0.90 \text{ watt,}$$

$$\text{terminal 2 is } P_2 = E_2 I_2 = 150 \times 0.005 = 0.75 \text{ watt,}$$

$$\text{terminal 3 is } P_3 = E_3 I_3 = 180 \times 0.030 = 5.4 \text{ watts.}$$

The total power supplied to the 3 loads is

$$0.90 + 0.75 + 5.4 = 7.05 \text{ watts.}$$

The total power supplied to the entire circuit including the voltage divider and the 3 loads is

$$9.15 + 7.05 = 16.2 \text{ watts.}$$

This value is checked as

$$P_t = E \times I_t = 270 \times 0.060 = 16.2 \text{ watts.}$$

In figure 5-5 the voltage divider resistances are given and the current in *R*5 is to be found. The load current in *R*1 is 6 ma.; the current in *R*2 is 4 ma.; and the current in *R*3 is 10 ma. The source voltage is 510 volts. Kirchhoff's Current Law may be applied at the junctions *a*, *b*, *c*, and *d* to determine expressions for the current in resistors *R*4, *R*5, *R*6, and *R*7. Accordingly, the current in *R*4 is $I + 6 + 4 + 10$, or $I + 20$; the current in *R*5 is I; the current in *R*6 is $I + 6$; the current in *R*7 is $I + 6 + 4$, or $I + 10$.

The voltage across *R*4 may be expressed in terms of the resistance in k-ohms and the current in milliamperes as $5(I + 20)$ volts. Similarly, the voltage across *R*5 is equal to $25I$; the voltage across *R*6 is $10(I + 6)$ and the voltage across *R*7 is $10\ (I + 10)$. Kirchhoff's law of voltages may be applied to the voltage divider to solve for the unknown current, I, by expressing the source voltage in terms of the given values of voltage, resistance, and current (both known and unknown values). The sum of the voltages across *R*4, *R*5, *R*6, and *R*7 is equal to the source voltage as follows:

$$E_4 + E_5 + E_6 + E_7 = E_s$$

$$5(I + 20) + 25I + 10(I + 6) + 10(I + 10) = 510$$

$$5I + 100 + 25I + 10I + 60 + 10I + 100 = 510$$

$$50I + 260 = 510$$

$$50I = 510 - 260$$

$$50I = 250$$

$$I = 5 \text{ ma.}$$

The current of 5 ma. through *R*5 produces a voltage drop across *R*5 of 5 x 25, or 125 volts.

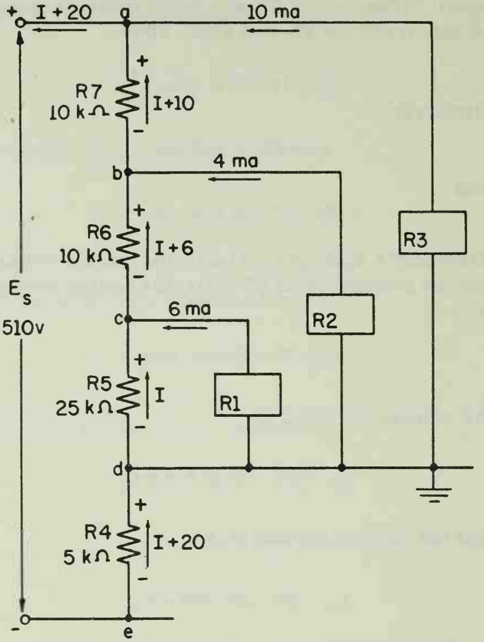


Figure 5-5.—Voltage divider, to determine E and R.

Since *R*1 is in parallel with *R*5, the voltage across load *R*1 is 125 volts. The current through *R*4 is 5 + 20, or 25 ma. and the corresponding voltage is 5 x 25, or 125 volts. Since point *d* is at ground potential, point *c* is 125 volts positive with respect to ground, whereas point *e* is 125 volts negative with respect to ground. The current in *R*6 is 5 + 6 or 11 ma. and the voltage drop across *R*6 is 11 x 10, or 110 volts. The current in *R*7 is 5 + 10, or 15 ma. and the voltage drop is 15 x 10 or 150 volts. The total voltage is the sum of the voltages across the divider. Thus,

$$125 + 125 + 110 + 150 = 510.$$

The power absorbed by each resistor in the voltage divider may be found by multiplying the voltage across the resistor by the current in the resistor. If the current is expressed in amperes and the e.m.f. in volts, the power will be expressed in watts. Thus the power in *R*4 is

$$P_4 = E_4 I_4 = 125 \times 0.025 = 3.125 \text{ watts.}$$

Similarly the power in $R5$ is 125 x 0.005 = 0.625 watts; the power in $R6$ is 110 x 0.011 = 1.21 watts; and in $R7$ is 150 x 0.015 = 2.25 watts. The total power in the divider is

$$3.125 + 0.625 + 1.21 + 2.25 = 7.21 \text{ watts.}$$

The voltage across load $R1$ is the voltage across $R5$, or 125 volts. The power in $R1$ is

$$P_1 = E_1 I_1 = 125 \times 0.006 = 0.750 \text{ watts.}$$

The voltage across load $R2$ is equal to the sum of the voltages across $R5$ and $R6$. Thus,

$$E_2 = E_5 + E_6 = 125 + 110 = 235 \text{ volts.}$$

The power in load $R2$ is

$$P_2 = E_2 I_2 = 235 \times 0.004 = 0.940 \text{ watts.}$$

The voltage across load $R3$ is equal to the sum of the voltages across $R5$, $R6$, and $R7$. Thus,

$$E_3 = E_5 + E_6 + E_7 = 125 + 110 + 150 = 385 \text{ volts.}$$

The power in load $R3$ is

$$P_3 = E_3 I_3 = 385 \times 0.010 = 3.85 \text{ watts,}$$

The total power in the three loads is

$$0.75 + 0.94 + 3.85 = 5.54 \text{ watts,}$$

and the total power supplied by the source is equal to the sum of the power absorbed by the voltage divider and the three loads, or

$$7.21 + 5.54 = 12.75 \text{ watts.}$$

The total power may be checked by

$$P_t = E_t I_t = 510 \times 0.025 = 12.75 \text{ watts.}$$

The resistances of load resistors $R1$, $R2$, and $R3$ are determined by means of Ohm's law as follows:

$$R_1 = \frac{E_1}{I_1} = \frac{125}{6} = 20.83 \text{ k-ohms,}$$

$$R_2 = \frac{E_2}{I_2} = \frac{235}{4} = 58.75 \text{ k-ohms,}$$

and

$$R_3 = \frac{E_3}{I_3} = \frac{385}{10} = 38.5 \text{ k-ohms.}$$

Attenuators

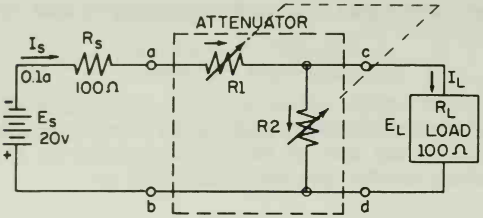
Attenuators are networks of resistors that are used to obtain the proper voltage, current, or power required by a load. They always reduce (attenuate) the source voltage to a lower value required by the load. Two of the simpler types of attenuators are the L and T types shown in figure 5-6.

If the device is adjustable, as shown, it is called an "attenuator"; if it is nonadjustable it is commonly called a "pad."

The L-type attenuator maintains constant resistance at ONE pair of terminals for any seting of the variable resistors. For example, in figure 5-6 (A), the resistance presented by the load and the attenuator to terminals *ab* should always be constant for any setting of ganged (grouped) resistors $R1$ and $R2$. This constant resistance must be equal to R_S in order to obtain maximum power transfer from the source to the attenuator and load.

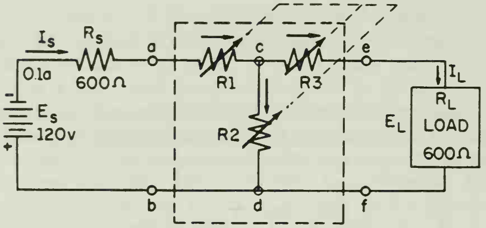
In figure 5-6 (A), the resistance offered to the flow of current through the terminals *a* and *b* includes (1) R_S and (2) R_1 acting in series with the parallel combination of $R2$ and R_L. In this circuit $R_S = R_L$, or

$$R_s = R_1 + \frac{R_2 R_L}{R_2 + R_L}$$



L ATTENUATOR

(A)



T ATTENUATOR

(B)

Figure 5-6.—L and T attenuators.

Thus it may be seen that $R1$ and $R2$ are adjusted so that

$$R_L = R_1 - \frac{R_2 R_L}{R_2 + R_L}$$

The resistance offered to the flow of current through terminals *c* and *d* includes (1) $R2$ acting in parallel with the series combination of $R1$ and R_s, and (2) R_L. The L attenuator operates properly only if the load is connected to terminals *cd* and the source to terminals *ab*. The load and the source are not interchangeable, because R_L is not equal to

$$\frac{R_2 (R_1 + R_s)}{R_2 + R_1 + R_s}.$$

The T-type attenuator, shown in figure 5-6 (B), maintains at BOTH pairs of terminals a constant resistance for any setting of the ganged variable resistor. As may be seen in the figure, an extra variable resistor is needed in the T-type attenuator, and the circuit is therefore more complicated than the L-type attenuator circuit.

In the T attenuator, the resistance offered to the flow of current through terminals *a* and *b* includes (1) R_s and (2) R_1 acting in series with the parallel combination, one branch of which is R_2 and the other branch of which is R_3 acting in series with R_L. In this circuit,

$$R_s = R_1 + \frac{R_2 (R_3 + R_L)}{R_2 + R_3 + R_L}.$$

The resistance offered to the flow of current through terminals *e* and *f* includes (1) R_3 in series with the parallel combination, one branch of which is $R2$ and the other branch of which is $R1$ acting in series with R_s and (2) R_L. In this circuit,

$$R_L = R_3 + \frac{R_2 (R_1 + R_s)}{R_2 + R_1 + R_3}.$$

Because $R_S = R_L$ and $R1 = R3$, the load and the source are interchangeable without affecting the operation of the T attenuator. Thus, the resistance offered to the flow of current through terminals *a* and *b* is equal to the resistance offered to the flow of current through terminals *e* and *f*.

There are other types of attenuators that are even more complicated—for example, ladder attenuators, so called because the circuit looks like a ladder; bridge-T attenuators, in which the two resistors forming the top member of the T are paralleled, or bridged, by another resistor; and decimal attenuators, in which the resistors are arranged so that the current or voltage may be reduced in steps equal to decimal fractions of the full-load values.

It is often desirable, especially in communication circuits, to lower the voltage applied to a load in order to attenuate the signal, and yet to permit the same amount of current to be drawn from the source as was drawn before the voltage across the load was lowered. Thus the load on the source remains constant and its characteristics are not altered when the load signal is weakened. The L-type of attenuator is one of the simplest circuits that may be used to accomplish this result.

L ATTENUATOR

In the L-type attenuator shown in figure 5-6 (A), the two objectives are: (1) To vary the load voltage, and (2) to maintain constant current through the source when the load voltage is varied. The source resistance is 100 ohms, the load resistance is 100 ohms, and the source voltage is 20 volts. Before the attenuator is inserted, the current delivered to the load is

$$I_s = \frac{E_s}{R_L + R_s} = \frac{20}{100 + 100} = 0.1 \text{ ampere.}$$

The load voltage in this case is $E_L = I_S R_L = 0.1 \times 100 = 10$ volts. The voltage lost in the source is 20 - 10 = 10 volts, which is the equivalent of 0.1 ampere flowing through the source resistance of 100 ohms.

To reduce the voltage across R_L, (fig. 5-6 (A)) to 5 volts and maintain the source current at 0.1 ampere, $R1$ and $R2$ are inserted. The current, I_L, through R_L is

$$I_L = \frac{E_L}{R_L} = \frac{5}{100} = 0.05 \text{ ampere.}$$

The current through $R1$ is 0.1 ampere, since it is in series with the source, and the voltage drop across $R1$ is the difference between the source voltage and the sum of the voltage drops in the source and across the load, or 20 - (10 + 5) = 5 volts. The resistance of $R1$ is $\frac{5}{0.1} = 50$ ohms.

The current through $R2$ is the difference between the source current of 0.1 ampere and the load current of 0.05 ampere, or 0.05 ampere. The voltage across $R2$ is 5 volts because it is in parallel with the load. The resistance of $R2$ is $\frac{5}{0.05} = 100$ ohms.

Thus, by inserting 50 ohms in series with the source and 100 ohms in shunt (parallel) with the load, the load voltage is reduced to 5 volts and the source current is maintained at 0.1 ampere. In this way the load on the source is maintained constant while the signal voltage at the load is reduced to one-half its original value.

The parallel resistance of $R2$ and R_L is 50 ohms and the total resistance of R1 in series with the parallel combination is 50 + 50, or 100 ohms. Thus, the same resistance is presented to the source after the insertion of R1 and $R2$ as before, and the load on the source remains the same.

T ATTENUATOR

In the T attenuator of figure 5-6 (B), R_S = 600 ohms, R_L = 600 ohms, and the source voltage is 120 volts. In this example, the attenuator is adjusted to reduce the load voltage to one-half its rated value. The problem is to find the necessary resistance values of $R1$, $R2$, and $R3$. Before the attenuator is inserted, the load current is equal to $\frac{120}{600 + 600} = 0.1$ ampere and the rated load voltage, E_L is 0.1 x 600 = 60 volts. The attenuator reduces the load voltage to $\frac{1}{2}$ of 60, or 30 volts.

The load current with 30 volts applied to the load will be $\frac{30}{600} = 0.05$ ampere. Since the total current must remain 0.1 ampere, the current through $R2$ will be 0.1 - 0.05 = 0.05 ampere.

The algebraic sum of the voltages around circuit *dcefd* is equal to zero, and these may be expressed in terms of current, resistance, and voltage as,

$$+0.05R_2 - 0.05R_3 - 30 = 0,$$

and since $R_3 = R_1$,

$$0.05R_2 - 0.05R_1 = 30. \qquad (5\text{-}1)$$

The algebraic sum of the voltages around circuit *bacdb* is equal to zero. Thus,

$$120 - 0.1 \times 600 - 0.1R_1 - 0.05R_2 = 0$$

$$0.05R_2 + 0.1R_1 = 60. \qquad (5\text{-}2)$$

Subtracting equation (5-1) from equation (5-2) and solving for $R1$,

$$0.05R_2 + 0.1R_1 = 60$$

$$0.05R_2 - 0.05R_1 = 30$$

$$0 + 0.15R_1 = 30$$

$$R_1 = 200 \text{ ohms} = R_3.$$

Substituting the value of $R1$ in equation (5-1),

$$0.05R_2 - 0.05(200) = 30$$

$$0.05R_2 = 40$$

$$R_2 = 800 \text{ ohms.}$$

The resistance to the flow of current through terminals *a* and *b* includes (1) the 600-ohm source and (2) the attenuator resistance, R_{ab}.

$$R_{ab} = R_1 + \frac{R_2(R_3 + R_L)}{R_2 + R_3 + R_L}$$

$$= 200 + \frac{800(200 + 600)}{800 + 200 + 600}$$

$$= 200 + 400$$

$$= 600 \text{ ohms.}$$

The resistance to the flow of current through terminals *e* and *f* includes (1) the 600-ohm load and (2) attenuator resistance, R_{ef}.

$$R_{ef} = R_3 + \frac{R_3(R_1 + R_s)}{R_2 + R_1 + R_s}$$

$$= 200 + \frac{800(200 + 600)}{800 + 200 + 600}$$

$$= 200 + 400$$

$$= 600 \text{ ohms.}$$

Thus, $R_{ef} = R_{ab}$ and both the load and the source see the same resistance "looking" into the T attenuator. The source current I_s is

$$\frac{E_s}{R_s + R_{ab}} = \frac{120}{600 + 600} = 0.1 \text{ ampere.}$$

The input voltage E_{ab} to the attenuator is

$$I_sR_{ab} = 0.1 \times 600 = 60 \text{ volts.}$$

The voltage drop across $R1$ is

$$I_sR_1 = 0.1 \times 200 = 20 \text{ volts.}$$

The voltage drop across $R2$ is

$$I_2R_2 = 0.05 \times 800 = 40 \text{ volts.}$$

The voltage drop across $R3$ is

$$I_3R_3 = 0.05 \times 200 = 10 \text{ volts.}$$

Thus, the voltage across the load is

$$40 - 10 = 30 \text{ volts.}$$

Bridge Circuits

THE SIMPLE RESISTANCE BRIDGE

A resistance bridge circuit in its simplest form is shown in figure 5-7. Two identical resistors, $R1$ and $R2$, are connected in parallel across a 20-volt power source. The network becomes a bridge circuit when a cross connection, or "bridge" is placed between the two resistors.

Voltage across both resistors is dropped at the same rate, because the resistors are identical. Therefore, points *a-a'*, *b-b'*, *c-c'*, and *d-d'* are at equal potentials. If the bridge is connected between points of equal potential, as in figure 5-7 (A), no current will flow through the bridge. However, if the bridge is connected between points of unequal potential, current will flow from the more negative to the less negative end, as shown in figure 5-7 (B). In (B), current flows right-to-left from b' to d. In (C), current flows left-to-right from a to c'. Thus, it can be seen that the direction of bridge current is controlled by the relative potential of the two ends of the bridge resistor. When the bridge is across equal potentials, and no current flows, it is said to be BALANCED. When it is across unequal potentials, and current tends to flow, it is said to be UNBALANCED. The bridge may be unbalanced in either or both of two ways—(1) by connecting the bridge to unequal potentials, or (2) by using resistors of unequal values, thus causing an unbalance.

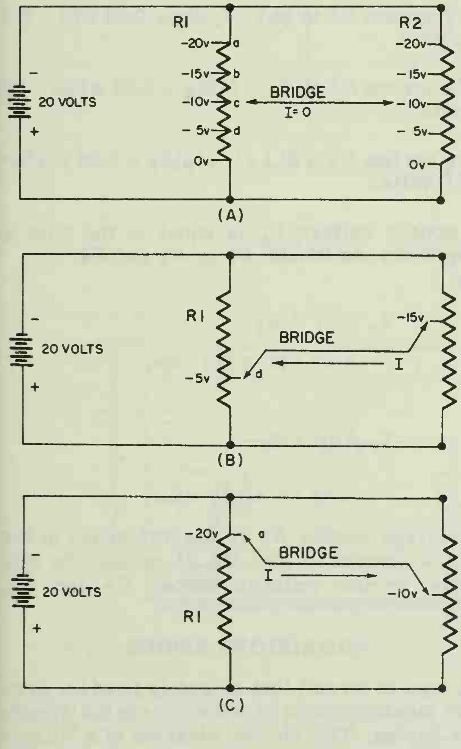


Figure 5-7.—Simple resistance bridges.

UNBALANCED RESISTANCE BRIDGE

Figure 5-8 shows an unbalanced bridge using unequal resistors. The two parallel legs are $R1$-$R4$ and $R3$-$R5$. $R2$ is the bridge. The current and voltage drop of each resistor, and the source voltage E_s, are to be determined.

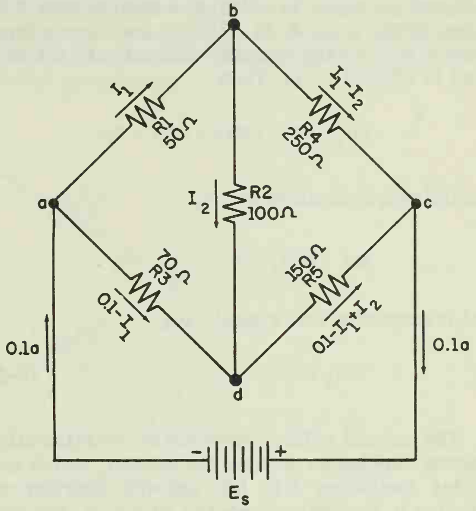


Figure 5-8.—Unbalance resistance bridge.

The current of 0.1 ampere flowing into junction a divides into two parts. The part flowing through $R1$ is indicated as I_1 and the part through $R3$ is $0.1 - I_1$. Similarly, at junction b, I_1 divides, part flowing through $R2$ and the remainder through R4. The part through R2 is designated I_2 and the part through $R4$ is $I_1 - I_2$. The direction of current through $R2$ may be assumed arbitrarily.

If the solution indicates a positive value for I_2 the assumed direction is proved to be correct. The current through $R4$ is $I_1 - I_2$. At junction d the currents may be analyzed in a similar manner. Current I_2 through $R2$ joins current $0.1 - I_1$, from $R3$; and the current through $R5$ is $0.1 - I_1 + I_2$.

The unknown currents, I_1 and I_2, may be determined by establishing two voltage equations in which they both appear. These equations are solved for I_1 and I_2 in terms of the given values of current and resistance. The first voltage equation is developed by tracing clockwise around the closed circuit containing resistors $R1$, $R2$, and $R3$. The trace starts at junction a, and proceeds to b, to d, and back to a. The algebraic sum of the voltages around this circuit is zero. These voltages are expressed in terms of resistance and current. Going from a to b, the voltage drop is in the direction of the arrow and is equal to $-50I_1$; the drop across $R2$, going from b to d, is $-100I_2$; and the voltage from d to a (in the opposite direction to the arrow) is $+70(0.1 - I_1)$. Thus,

$$-50I_1 - 100I_2 + 70(0.1 - I_1) = 0.$$

Multiplying both sides by -1,

$$50I + 100I_2 - 70(0.1 - I_1) = 0,$$

and transposing and simplifying,

$$120I_1 + 100I_2 = 7. \qquad (5\text{-}3)$$

The second voltage equation is established by tracing clockwise around the circuit, which includes resistors $R4$, $R5$, and $R2$. Starting at junction b, the trace proceeds to c, to d, and returns to b. The voltage across $R4$, from b to c, is $-250(I_1 - I_2)$; the voltage across $R5$, from c to d, is $+150(0.1 - I_1 + I_2)$; and the voltage across $R2$, from d to b, is $+100I_2$. Thus,

$$-250(I_1 - I_2) + 150(0.1 - I_1 + I_2) + 100I_2 = 0$$

from which,

$$400I_1 - 500I_2 = 15. \qquad (5\text{-}4)$$

Equations (5-3) and (5-4) may be solved simultaneously by multiplying equation (5-3) by the factor 5 and then adding the equations to eliminate I_2 as follows:

$$\begin{aligned} 400I_1 - 500I_2 &= 15 \\ 600I_1 + 500I_2 &= 35 \\ \hline 1{,}000I_1 &= 50 \\ I_1 &= 0.05 \text{ ampere.} \end{aligned}$$

Substituting the value of 0.05 for I_1 in equation (5-3) and solving for I_2,

$$\begin{aligned} 120(0.05) + 100I_2 &= 7 \\ 100I_2 &= 1 \\ I_2 &= 0.01 \text{ ampere.} \end{aligned}$$

Thus the current in $R1$ is $I_1 = 0.05$ ampere. The current in $R2$ is $I_2 = 0.01$ ampere. The current in $R3$ is $0.1 - I_1 = 0.1 - 0.05$, or 0.05 ampere. The current in $R4$ is $I_1 - I_2 = 0.05 - 0.01$, or 0.04 ampere. The current in $R5$ is $0.1 - I_1 + I_2 = 0.1 - 0.05 + 0.01 = 0.06$ ampere. The voltages E_1, E_2, E_3, E_4, and E_5 are as follows:

E_1 across $R1$ is $I_1R_1 = 0.05 \times 50 = 2.5$ volts.

E_2 across $R2$ is $I_2R_2 = 0.01 \times 100 = 1.0$ volts.

E_3 across $R3$ is $(0.1 - I_1)R_3 = 0.05 \times 70 = 3.5$ volts.

E_4 across $R4$ is $(I_1 - I_2)R_4 = 0.04 \times 250 = 10$ volts.

E_5 across $R5$ is $(0.1 - I_1 + I_2)R_5 = 0.06 \times 150 = 9.0$ volts.

The source voltage E_s is equal to the sum of voltages across $R3$ and $R5$ or $R1$ and $R4$. Thus,

$$\begin{aligned} E_s &= E_1 + E_4 \\ &= 2.5 + 10 = 12.5 \text{ volts,} \end{aligned}$$

and

$$\begin{aligned} E_s &= E_3 + E_5 \\ &= 3.5 + 9 = 12.5 \text{ volts.} \end{aligned}$$

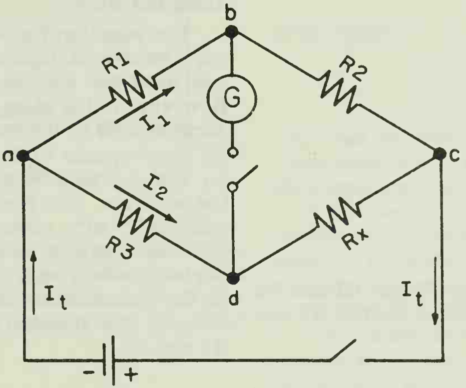
The voltage across $R2$ is the difference in the voltages across $R3$ and $R1$. It is also the difference in the voltages across $R4$ and $R5$.

WHEATSTONE BRIDGE

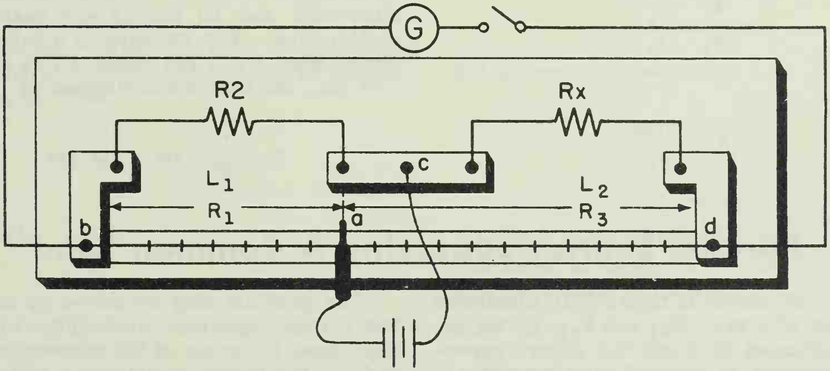
A type of circuit that is widely used for precision measurements of resistance is the Wheatstone bridge. The circuit diagram of a Wheatstone bridge is shown in figure 5-9 (A). $R1$, $R2$, and $R3$ are precision variable resistors, and R_x

is the resistor whose unknown value of resistance is to be determined. After the bridge has been properly balanced, the unknown resistance may be determined by means of a simple formula. The galvanometer, G, is inserted across terminals b and d to indicate the condition of balance. When the bridge is properly balanced there is no difference in potential across terminals bd, and the galvanometer deflection, when the switch is closed, will be zero.

The operation of the bridge is explained in a few logical steps. When the switch to the battery is closed, electrons flow from the negative terminal of the battery to point a. Here the current divides, as it would in any parallel circuit, a part of it passing through $R1$ and $R2$ and the remainder passing through $R3$ and R_x. The two currents, labeled I_1 and I_2, unite at point c and return to the positive terminal of the battery. The value of I_1 depends on the sum of resistances R_1 and R_2, and the value of I_2 depends on the sum of resistances R_3 and R_x. In each case, according to Ohm's law, the current is inversely proportional to the resistance.



(A)
SCHEMATIC WHEATSTONE-BRIDGE CIRCUIT



(B)
SLIDE-WIRE BRIDGE

Figure 5-9.—Wheatstone bridge circuit.

$R1$, $R2$, and $R3$ are adjusted so that when the galvanometer switch is closed there will be no deflection of the needle. When the galvanometer shows no deflection there is no difference of potential between points *b* and *d*. This means that the voltage drop (E_1) across $R1$, between points *a* and *b*, is the same as the voltage drop (E_3) across $R3$, between points *a* and *d*. By similar reasoning, the voltage drops across $R2$ and R_x—that is, E_2 and E_x—are also equal. Expressed algebraically,

$$E_1 = E_3,$$

or

$$I_1R_1 = I_2R_3,$$

and

$$E_2 = E_x,$$

or

$$I_1R_2 = I_2R_x.$$

Dividing the voltage drops across $R1$ and $R3$ by the respective voltage drops across R2 and R_x,

$$\frac{I_1R_1}{I_1R_2} = \frac{I_2R_3}{I_2R_x}.$$

Simplifying,

$$\frac{R_1}{R_2} = \frac{R_3}{R_x}.$$

Therefore,

$$R_x = \frac{R_2R_3}{R_1}.$$

The resistance values of $R1$, $R2$, and $R3$ are readily determined from the markings on the standard resistors, or from the calibrated dials if a dial-type bridge is used.

The Wheatstone bridge may be of the slide-wire type, as shown in figure 5-9 (B). In the slide-wire circuit, the slide-wire (b to d), corresponds to R_1 and R_3 of figure 5-9 (A). The wire may be an alloy of uniform cross section; for example German silver or nichrome, having a resistance of about 100 ohms. Point *a* is established where the slider contacts the wire. The bridge is balanced by moving the slider along the wire.

The equation for solving for R_x in the slide-wire bridge of figure 5-9 (B), is similar to the one used for solving for R_x in figure 5-9 (A). However, in the slide-wire bridge the length L_1 corresponds to the resistance R_1, and the length L_2 corresponds to the resistance R_3. Therefore, L_1 and L_2 may be substituted for R_1 and R_3 in the equation. The resistance of L_1 and L_2 varies uniformly with slider movement because in a wire of uniform cross section the resistance varies directly with the length; therfore the ratio of the resistances equals to the corresponding ratio of the lengths. Substituting L_1 and L_2 for R_1 and R_3

$$R_x = \frac{L_2R_2}{L_1}.$$

A meter stick is mounted underneath the slide-wire and L1 and L2 are easily read in centimeters. For example, if a balance is obtained when R2 - 150 ohms, L1 25 cm. and L2 = 75 cm., the unknown resistance is

$$R_x = \frac{75}{25} \times 150 = 450 \text{ ohms.}$$

Parallel Sources Supplying A Common Load

The circuit shown in figure 5-10 illustrates two sources of e.m.f., E_{s1} and E_{s2}, having internal resistances of 2 and 2.5 ohms respectively, connected in parallel, and supplying a 5-ohm load. Neglecting the resistance of the lead wires, it is desired to determine the current delivered by each source to the load, the load current, and the load voltage.

The problem may be solved by establishing two voltage equations in which the voltages are expressed in terms of the unknown currents I_1 and I_2, the known resistances, and the known voltages. The equations are then solved simultaneously as in previous examples, to eliminate one of the unknown currents. The other unknown current is solved by substitution.

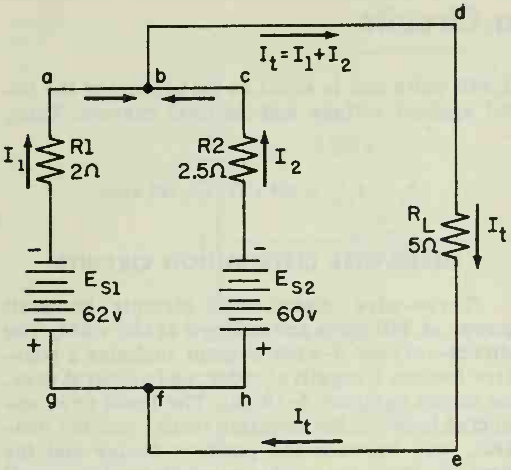


Figure 5-10.—Parallel sources supplying a common load.

The first voltage equation is established by starting at point g and tracing clockwise around circuit *gabdefg*. The total load current is equal to the sum of the source currents, $I_1 + I_2$. The first voltage equation is,

$$62 - 2I_1 - 5(I_1 + I_2) = 0,$$

from which,

$$7I_1 + 5I_2 = 62. \qquad (5\text{-}5)$$

The second voltage equation is established by starting at point h and tracing around circuit *hcbdefh*. Thus,

$$60 - 2.5I_2 - 5(I_1 + I_2) = 0,$$

from which,

$$5I_1 + 7.5I_2 = 60. \qquad (5\text{-}6)$$

I_2 is eliminated by multiplying equation (5-5) by 1.5 and subtracting equation (5-6) from the result, as follows:

$$\begin{aligned} 10.5I_1 + 7.5I_2 &= 93 \\ \underline{5.0I_1 + 7.5I_2} &\underline{= 60} \\ 5.5I_1 &= 33 \\ I_1 &= 6 \text{ amperes.} \end{aligned}$$

Substituting this value in equation (5-5),

$$7 \times 6 + 5I_2 = 62,$$

from which

$$I_2 = 4 \text{ amperes.}$$

The load current is $I_1 + I_2 = 6 + 4 = 10$ amperes. Thus source E_{s1} supplies 6 amperes and source E_{s2} supplies 4 amperes.

The load voltage is equal to the voltage developed across terminals f and b and is equal to the difference in a given source voltage and the internal voltage absorbed across the corresponding source resistance.

The statement applies equally to either source since both are in parallel with the load. In terms of source E_{s1}

$$\begin{aligned} E_{fb} &= E_{s1} - I_1R_1 \\ &= 62 - 6 \times 2 \\ &= 50 \text{ volts,} \end{aligned}$$

and in terms of source E_{s2}

$$\begin{aligned} E_{fb} &= E_{s2} - I_2R_2 \\ &= 60 - 4 \times 2.5 \\ &= 50 \text{ volts.} \end{aligned}$$

A further check on the load voltage is to express this value in terms of the load current and the load resistance as follows:

$$\begin{aligned} E_{fb} &= (I_1 + I_2)\, R_L \\ &= (6 + 4)\ (5) \\ &= 50 \text{ volts.} \end{aligned}$$

Distribution Circuits

TWO-WIRE DISTRIBUTION CIRCUITS

Up to this point the voltage drop and the power lost in the line wires connecting the load and the source have been neglected. When the load is located at some distance from the source, the line resistance becomes an appreciable part of the total circuit resistance and the voltage and power lost in the line become significant even with moderate loads.

In figure 5-11, load *M* draws 7 amperes through terminals *b* and *e*, and the parallel group of lamps draws 5 amperes through terminals *c* and *d*. The current in line wires *bc* and *de* is 5 amperes. The line current in wires *ab* and *ef* is 5 + 7 = 12 amperes.

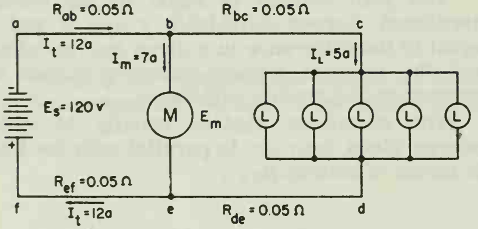


Figure 5-11.—Simple two-wire distribution circuit.

The voltage source supplies a constant potential of 120 volts between points *a* and *f*. The resistance of line wires *ab* and *ef* is 2 x 0.05 = 0.1 ohm. The voltage drop across line wires *ab* and *ef* is 12 x 0.1 = 1.2 volts. The voltage drop across line wires *bc* and *de* is 5 x 0.1 = 0.5 volt. The voltage across *M* is 120 - 1.2 = 118.8 volts and the voltage across the five lamps is 118.8 - 0.5 = 118.3 volts.

The power dissipated in line wires *ab* and *ef* is equal to $(12)^2 \times 0.1 = 144.4$ watts. The power absorbed by line wires *bc* and *de* is $(5)^2 \times 0.1 = 2.5$ watts. The total power absorbed by the line wires is 14.4 + 2.5 = 16.9 watts.

The power delivered to load *M* is 118.8 x 7 = 831.6 watts, and to the 5 lamps is 118.3 x 5 = 591.5 watts. The total power supplied to the entire circuit is equal to 16.9 + 831.6 + 591.5 = 1,440 watts and is equal to the product of the total applied voltage and the total current. Thus,

$$P_t = E_t I_t = 120 \times 12 = 1{,}440 \text{ watts.}$$

THREE-WIRE DISTRIBUTION CIRCUITS

Three-wire distribution circuits transmit power at 240 volts and utilize it at 120 volts. The direct-current 3-wire system includes a positive feeder, a negative feeder, and a neutral wire, as shown in figure 5-12 (A). The loads are connected between the negative feeder and the neutral, and between the positive feeder and the neutral. When the loads are unbalanced (unequal) the neutral wire carries a current equal to the difference in the currents in the negative and positive feeders.

In the example of figure 5-12 (A), load *L*1 draws 10 amperes, load *L*2 draws 4 amperes, and the neutral wire carries a current of 10 - 4 = 6 amperes. The direction of flow of the current in the neutral wire is always the same as that of the smaller of the currents in the positive and negative feeders. Thus the flow is to the left in the lower (positive) wire and also in the neutral. The current in the upper (negative) wire is 10 amperes and in the lower wire is 4 amperes. The algebraic sum of the currents entering and leaving junction *c* is equal to zero. Thus,

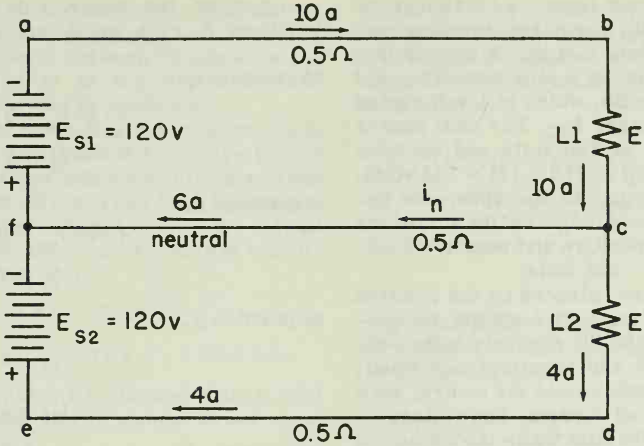
$$+10 - 6 - 4 = 0.$$

To find load voltage, E_1, a voltage equation is established in which E_1 is expressed in terms of the source voltage, E_{S1}, and the *IR* drops in the negative feeder and neutral wire. The algebraic sum of the voltages around the circuit *fabcf*, is equal to zero. Starting at *f* and proceeding clockwise,

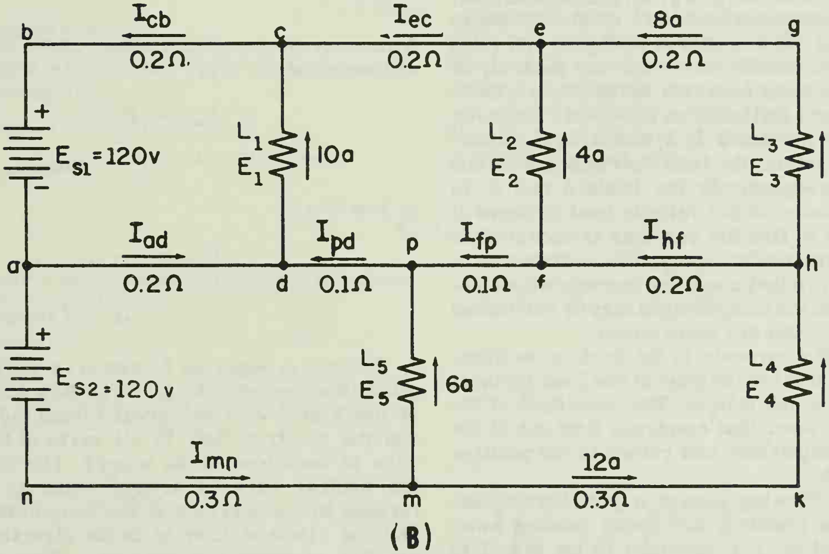
$$+120 - 10 \times 0.5 - E_1 - 6 \times 0.5 = 0$$

$$E_1 = 112 \text{ volts.}$$

Thus the voltage across load *L*1 is 112 volts. This voltage is less than the source voltage by an amount equal to the sum of the voltage drops in


a
10 a
0.5Ω
b
E_{S1} = 120v
L1
E_1
10 a
6a
i_n
f
neutral
0.5Ω
c
E_{S2} = 120v
L2
E_2
4a
4a
e
0.5Ω
d

(A)
TWO LOADS


I_{cb}
b
0.2Ω
c
I_{ec}
0.2Ω
e
8a
0.2Ω
g
E_{S1}=120v
L_1
E_1
10a
L_2
E_2
4a
L_3
E_3
8a
I_{ad}
a
0.2Ω
d
I_{pd}
0.1Ω
p
I_{fp}
0.1Ω
f
I_{hf}
0.2Ω
h
E_{S2}=120 v
L_5
E_5
6a
L_4
E_4
12a
I_{mn}
n
0.3Ω
m
12a
0.3Ω
k

(B)
FIVE LOADS

Figure 5-12.—Three-wire distribution circuits.

the negative (5 volts) and the neutral (3 volts) wires.

To find load voltage E_2 a voltage equation is established in which E_2 is expressed in terms of the source voltage, E_{S2}, and the *IR* drops in the positive feeder and the neutral wire. The algebraic sum of the voltages around the circuit *efcde* is zero. Starting at *e* and proceeding clockwise,

$$+120 + (6 \times 0.5) - E_2 - (4 \times 0.5) = 0$$

$$E_2 = 121 \text{ volts}.$$

In tracing the circuit from *f* to *c* note that the direction is against the arrow representing current flow, and therefore that the *IR* drop of (6 x 0.5) volts is preceded by a plus sign. The load voltage, E_2, is 121 volts, which is 1 volt higher than the source voltage, E_{s2}. The total source voltage ($E_{s1} + E_{s2}$) is 240 volts and the total load voltage ($E_1 + E_2$) is 112 + 121 = 233 volts. This value is also equal to the difference between the total source voltage and the sum of the voltage drops in the positive and negative feeders, or 240 - (2 + 5) = 233 volts.

When the loads are balanced on the positive and negative sides of the 3-wire system, the neutral current is zero and the currents in the outside wires (positive and negative) are equal. When the loads are unbalanced the neutral wire carries the unbalanced current. The voltage on the heavily loaded side falls while the voltage on the lightly loaded side rises. The lower the resitance of the neutral wire, the less unbalance in voltage there will be for a given unbalanced load.

A more complicated 3-wire circuit is shown in figure 5-12 (B). The source voltage is 120 volts between each outside wire and the neutral, or center, wire. Load currents in the upper side of the system are indicated as 10, 4, and 8 amperes respectively for loads 1, 2, and 3. In the lower side of the system, the load currents are 12 and 6 amperes respectively for loads 4 and 5. In order to determine the various load voltages it is necessary to find the currents in each outside wire and in the neutral wire. The resistances of these wires are indicated, and therefore the voltage drops and the load voltages may be calculated after the currents are determined.

To find the currents in the various sections of the wires, it is best to start at the load farthest removed from the source. The polarities of the sources are such that electrons flow out of the negative terminal at *n* and return to the positive terminal at *b*.

Currents flowing toward a junction are assumed to be positive, and those flowing away from a junction are assumed to be negative. Applying Kirchhoff's Current Law at junction *h*, the neutral current, I_n (flowing from *h* to *f*) is determined as

$$12 - 8 - I_{hf} = 0$$

$$I_{hf} = 4 \text{ amperes.}$$

Applying the same rule successively to junctions *f*, *e*, *p*, *m*, *d*, and *c*, it follows that:

at junction *f*,

$$4 - 4 - I_{fp} = 0$$

$$I_{fp} = 0 \text{ ampere,}$$

at junction *e*,

$$4 + 8 - I_{ec} = 0$$

$$I_{ec} = 12 \text{ amperes,}$$

at junction *p*,

$$6 + 0 - I_{pd} = 0$$

$$I_{pd} = 6 \text{ amperes,}$$

at junction *m*,

$$+ I_{mn} - 6 - 12 = 0$$

$$I_{mn} = 18 \text{ amperes,}$$

at junction *d*,

$$I_{ad} + 6 - 10 = 0$$

$$I_{ad} = 4 \text{ amperes,}$$

at junction *c*,

$$I_{cb} + 10 + 12 = 0$$

$$I_{cb} = 22 \text{ amperes.}$$

Thus, E_{s1} supplies 22 amperes and E_{s2} supplies 18 amperes. The electron flow in all parts of the lower wire is outward from the source, and the electron flow in all parts of the upper wire is back toward the source. The current in the neutral wire is always equal to the difference in the currents in the two outside wires, and the electron flow is in the direction of the smaller of these two currents. Thus in figure 5-12 (B), the neutral current in section *ad* is 4 amperes, which is the difference between 18 amperes and 22 amperes; and it is in the direction of the smaller current in section *nm*. The neutral current in section *pd* is 6 amperes, which is the difference between 18 amperes and 12 amperes; and it is in the same direction as the 12 amperes in section *ec*. The neutral current in section *fp* is zero because the current in each outside wire in that section is 12 amperes. The neutral current in section *hf* is 4 amperes, which is the difference between 12 amperes and 8 amperes, and it is in the direction of the smaller outside current in section *ge*.

In order to find the voltages across the loads in figure 5-12 (B), Kirchhoff's Voltage Law is applied to the various individual circuits. Thus to find the voltage, E_1, across load L_1, the algebraic sum of the voltages around the circuit *abcda* is equated to zero, and E_1 is then readily determined. Starting at *a*,

$$-120 + (22 \times 0.2) + E_1 + (4 \times 0.2) = 0$$

$$E_1 = 114.8 \text{ volts.}$$

To find load voltage E_2, the algebraic sum of the voltages around circuit *dcefpd* is set equal to zero. Starting at *d*,

$$-114.8 + (12 \times 0.2) + E_2 + (0 \times 0.1) - (6 \times 0.1) = 0$$

$$E_2 = 113 \text{ volts.}$$

To find load voltage E_3, the algebraic sum of the voltages around loop *feghf* is set equal to zero. Starting at *f*,

$$-113 + (8 \times 0.2) + E_3 - (4 \times 0.2) = 0$$

$$E_3 = 112.2 \text{ volts.}$$

To find load voltage E_4, the algebraic sum of the voltages around loop *nadpfhkmn* is set equal to zero. Loop *mpfhkm* cannot be used because it would contain two unknown voltages, E_5 and E_4. Starting at *n*,

$$-120 - (4 \times 0.2) + (6 \times 0.1) + (0 \times 0.1) + (4 \times 0.2) + E_4$$

$$+ (12 \times 0.3) + (18 \times 0.3) = 0$$

$$E_4 = 110.4 \text{ volts.}$$

To find load voltage E_5, the algebraic sum of the voltages around loop *nadpmn* is set equal to zero. Starting at *n*,

$$-120 - (4 \times 0.2) + (6 \times 0.1) + E_5 + (18 \times 0.3) = 0$$

$$E_5 = 114.8 \text{ volts.}$$

In each case, the equations used contain one unknown; and thus a simple solution is quickly obtained. It is necessary that the path traced include a completely closed loop and that all but one of the voltages within that loop be known. Simple transposition of the resulting equation gives the desired voltage.

QUIZ

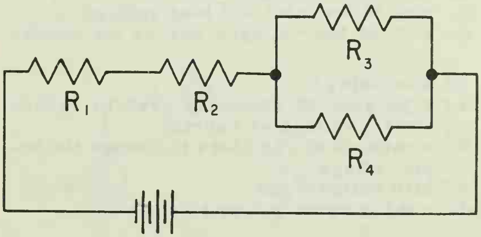
1. The minimum number of resistors in a compound circuit is/are
   a. four
   b. three
   c. two
   d. one
2. Total resistance of the circuit shown is determined by the formula

   a. $R_1R_2 + \dfrac{R_3R_4}{R_4 + R_3}$

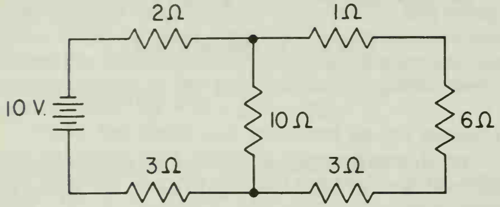
   b. $R_1 + R_2 + \dfrac{R_3 + R_4}{R_3R_4}$

   c. $R_1 + R_2 + \dfrac{R_3R_4}{R_3 + R_4}$

   d. $R_1 + R_2 \left(\dfrac{R_3R_4}{R_3 + R_4}\right)$



3. In the circuit below -- what is the value of I_t?
   a. I_t = 1.14 amp
   b. I_t = 0.4 amp
   c. I_t = 0.667 amp
   d. I_t = 1 amp



4. In the circuit in question 3, how much power is consumed by the 6-ohm resistor?
   a. 15 watts
   b. 1.5 watts
   c. 60 watts
   d. 6 watts

5. A voltage divider is used to
   a. provide different voltage values for multiple loads from a single source
   b. provide several voltage drops in parallel
   c. increase the voltage to the load at several taps
   d. provide tap points to alter power supplied

6. The total power supplied to the entire circuit by a voltage divider and 4 loads is the
   a. sum of the 4 loads
   b. voltage divider minus 4 loads
   c. voltage divider plus the 4 loads
   d. voltage divider only

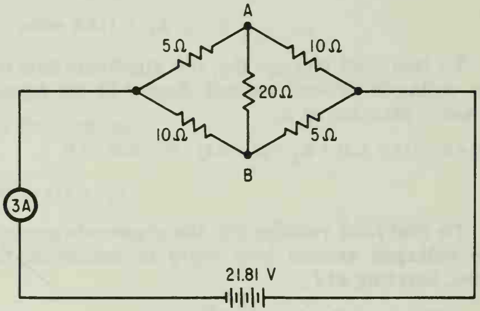
7. The total voltage of a voltage divider is the
   a. input voltage minus the load's voltages
   b. the load's voltages only
   c. sum of the input and load voltage
   d. sum of the voltages across the divider

8. An attenuator is
   a. a network of resistors used to reduce power, voltage or current
   b. a network of resistors to change the input voltage
   c. also called a pad
   d. used in every power circuit

9. In an attenuator, the resistors are
   a. adjusted separately
   b. connected in parallel with the load
   c. connected in series with the load
   d. ganged

10. What two conditions may be observed in a bridge circuit?
    a. T and L network characteristics
    b. No-load and full-load bridge current
    c. Unequal potential and unequal current
    d. Balance and unbalance

11. In the circuit below—how much current flows in the 20θ resistor and what is its direction?
    a. 26 a., B to A
    b. 1 a., A to B
    c. 0.26 a., A to B
    d. 1 a., B to A



12. In a three-wire distribution system, an unbalanced situation is indicated by the
    a. potential of the positive wire being equal to the negative wire
    b. positive wire carrying more amperage than the negative wire
    c. current in the neutral wire
    d. neutral wire carrying the total current

13. In figure 5-9 (A), the galvanometer will show zero deflection when

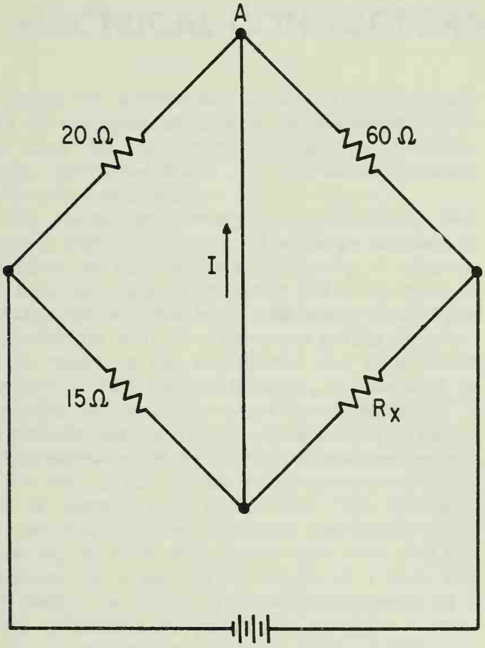
    a. $\frac{R_1}{R_2} = \frac{R_3}{R_x}$

    b. $R_x = \frac{R_1 R_3}{R_2}$

    c. $\frac{I_1 R_1}{I_2 R_x} = \frac{I_2 R_3}{I_1 R_2}$

    d. $R_x = \frac{R_1 R_2}{R_3}$

14. In the Wheatstone bridge type circuit below, the bridge current is toward point A. The resistance of R_x is
a. 30θ
b. greater than 45θ
c. 20θ
d. less than 15θ



15. In the slide-wire bridge, shown in figure 5-9 (B), L_1 is equal to

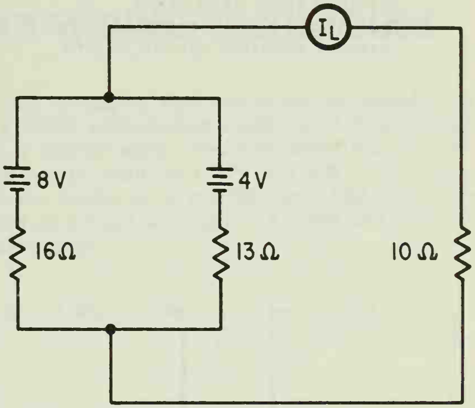
a. $L_1 = \frac{R_2 L_2}{R_1}$

b. $L_1 = \frac{R_1 + L_2}{R_2}$

c. $\frac{R_2}{R_1 L_2} = L_1$

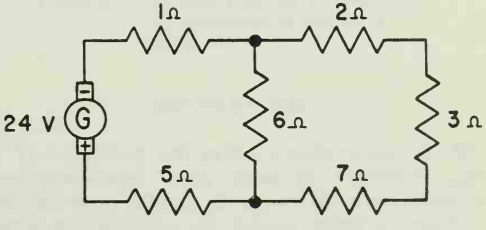
d. $\frac{R_1 L_2}{R_2} = L_1$

16. In the circuit below I line is
a. 4.44 a.
b. 0.444 a.
c. 0.522 a.
d. 5.22 a.



17. When checking a 3-wire distribution circuit going against the direction of current flow the IR drop is always
a. negative
b. positive
c. not used
d. always in direction of current flow

18. In the circuit below, the voltage drop across the 3-ohm resistor is
a. 2.4 volts
b. 24 volts
c. 9.6 volts
d. 0.96 volts



19. The resistance of the wire is taken into consideration in the 2- and 3-wire distribution systems because the
   a. source and load are very close
   b. resistance of the wire is the same throughout
   c. load and source are at a considerable distance from each other
   d. load must be decreased in order to determine accurate circuit values

20. What is Kirchhoff's second law as applied to 3-wire distribution circuits?
   a. Sum of all the voltages is zero
   b. Algebraic sum of all the voltages about a closed path is zero
   c. Alegbraic sum of all voltage is zero
   d. All IR drops in the circuit are negative

CHAPTER 6

ELECTRICAL CONDUCTORS AND WIRING TECHNIQUES

Since all electrical circuits utilize conductors of one type of another, it is essential that you know the basic physical features and electrical characteristics of the most common types of conductors.

As stated previously, any substance that permits the free motion of a large number of electrons is classed as a conductor. A conductor may be made from many different types of metals, but only the most commonly used types of materials will be discussed in this chapter.

To compare the resistance and size of one conductor with that of another, a standard or unit size of conductor must be established. A convenient unit of linear measurement, as far as the diameter of a piece of wire is concerned, is the mil (0.001 of an inch); and a convenient unit of wire length is the foot. The standard unit of size in most cases is the MIL-FOOT. That is, a wire will have unit size if it has diameter of 1 mil and a length of 1 foot. The resistance in ohms of a unit conductor of a given substance is called the specific resistance, or specific resistivity, of the substance.

Gage numbers are a further convenience in comparing the diameter of wires. The gage commonly used is the American wire gage (AWG), formerly the Brown and Sharpe (B and S) gage.

SQUARE MIL

The square mil is a convenient unit of cross-sectional area for square or rectangular conductors. A square mil is the area of a square, the sides of which are 1 mil, as shown in figure 6-1 (A). To obtain the cross-sectional area in square mils of a square conductor, square one side measured in mils. To obtain the cross-sectional area in square mils of a rectangular conductor, multiply the length of one side by that of the other, each length being expressed in mils.

For example, find the cross-sectional area of a large rectangular conductor 3/8 inch thick and 4 inches wide. The thickness may be expressed in mils as 0.375 x 1,000 = 375 mils, and the width as 4 x 1,000, or 4,000 mils. The cross-sectional area is 375 x 4,000, or 1,500,000 square mils.

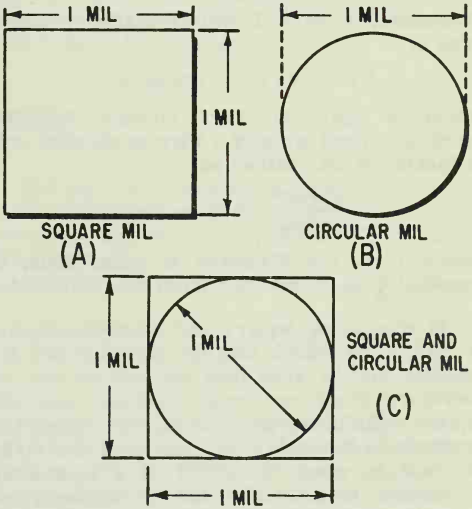


Figure 6-1.—(A) Square mil; (B) circular mil; (C) comparison of circular to square mil.

CIRCULAR MIL

The circular mil is the standard unit of wire cross-sectional area used in American and English wire tables. Because the diameters of round conductors, or wires, used to conduct electricity may be only a small fraction of an inch, it is convenient to express these diameters in mils, to avoid the use of decimals. For example, the diameter of a wire is expressed as 25 mils instead of 0.025 inch. A circular mil is the area of a circle having a diameter of 1 mil, as shown in figure 6-1 (B). The area in circular mils of a round conductor is obtained by squaring the diameter measured in mils. Thus, a wire having a diameter of 25 mils has an area of 25^2 or 625 circular mils. By way of comparison, the basic formula for the area of a circle is $A = \pi R^2$ and in this example the area in square inches is

$$A = \pi R^2 = 3.14(0.0125)^2 = 0.00049 \text{ sq. in.}$$

If D is the diameter of a wire in mils, the area in square mils is

$$A = \pi \left(\frac{D}{2}\right)^2 = \frac{3.1416}{4} D^2 = 0.7854D^2 \text{ sq. mils.}$$

Therefore, a wire 1 mil in diameter has an area of

$$A = 0.7854 \times 1^2 = 0.7854 \text{ sq. mils,}$$

which is equivalent to 1 circular mil. The cross-sectional area of a wire in circular mils is therefore determined as

$$A = \frac{0.7854D^2}{0.7854} \quad D^2 \text{ circular mils,}$$

where D is the diameter in mils. Thus, the constant $\frac{\pi}{4}$ is eliminated from the calculation.

In comparing square and round conductors it should be noted that the circular mil is a smaller unit of area than the square mil, and therefore there are more circular mils than square mils in any given area. The comparison is shown in figure 6-1 (C). The area of a circular mil is equal to 0.7854 of a square mil. Therefore, to determine the circular-mil area when the square-mil area is given, divide the area in square mils by 0.7854. Conversely, to determine the square-mil area when the circular-mil area is given, multiply the area in circular mils by 0.7854.

For example, a No. 12 wire has a diameter of 80.81 mils. What is (1) its area in circular mils and (2) its area in square mils?

Solution:

(1) $A = D^2 = 80.81^2 = 6{,}530$ circular mils.

(2) $A = 0.7854 \times 6{,}530 = 5{,}128.7$ square mils.

A rectangular conductor is 1.5 inches wide and 0.25 inch thick. (1) What is its area in square mils? (2) What size of round conductor in circular mils is necessary to carry the same current as the rectangular bar?

Solution:

(1) $1.5'' = 1.5 \times 1{,}000 = 1{,}500$ mils

$0.25'' = 0.25 \times 1{,}000 = 250$ mils

$A = 1{,}500 \times 250 = 375{,}000$ square mils.

(2) To carry the same current, the cross-sectional area of the rectangular bar and the cross-sectional area of the round conductor must be equal. There are more circular mils than square mils in this area, and therefore

$$A = \frac{375{,}000}{0.7854} = 477{,}000 \text{ circular mils.}$$

A wire in its usual form is a slender rod or filament of drawn metal. In large sizes, wire becomes difficult to handle, and its flexibility is increased by stranding. The strands are usually single wires twisted together in sufficient numbers to make up the necessary cross-sectional area of the cable. The total area in circular mils is determined by multiplying the area of one strand in circular mils by the number of strands in the cable.

CIRCULAR-MIL-FOOT

A circular-mil-foot, as shown in figure 6-2, is actually a unit of volume. It is a unit conductor 1 foot in length and having a cross-sectional area of 1 circular mil. Because it is considered a unit conductor, the circular-mil-foot is useful in making comparisons between wires that are made of different metals. For example, a basis of comparison of the RESISTIVITY (to be treated later) of various substances may be made by determining the resistance of a circular-mil-foot of each of the substances.

In working with certain substances it is sometimes more convenient to employ a different unit volume. Accordingly, unit volume may also be taken as the centimeter cube; and specific resistance becomes the resistance offered by a cube-shaped conductor 1 cm. long and 1 sq. cm. in cross-sectional area. The inch cube may also be used. The unit of volume employed is given in tables of specific resistances.

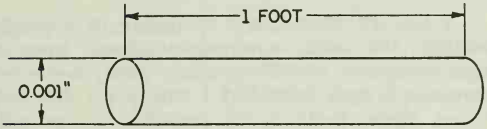


Figure 6-2.—Circular-mil-foot.

SPECIFIC RESISTANCE OR RESISTIVITY

Specific resistance, or resistivity, is the resistance in ohms offered by unit volume (the circular-mil-foot) of a substance to the flow of electric current. Resistivity is the reciprocal of conductivity. A substance that has a high resistivity will have a low conductivity, and vice versa.

Thus, the specific resistance of a substance is the resistance of a unit volume of that substance. Many tables of specific resistance are based on the resistance in ohms of a volume of the substance 1 foot long and 1 circular mil in cross-sectional area. The temperature at which the resistance measurement is made is also specified. If the kind of metal of which a conductor is made is known, the specific resistance of the metal may be obtained from a table. The specific resistances of some common substances are given in table 6-1.

The resistance of a conductor of uniform cross section varies directly as the product of the length and the specific resistance of the conductor and inversely as the cross-sectional area of the conductor. Therefore the resistance of a conductor may be calculated if the length, cross-sectional area, and specific resistance of the substance are known. Expressed as an equation, the resistance, R in ohms, of a conductor is

$$R = \rho\frac{L}{A},$$

where ρ (Greek rho) is the specific resistance in ohms per circular-mil-foot, L the length in feet (in the direction of current flow), and A the cross-sectional area in circular mils.

Table 6-1.—Specific Resistance.

Substance	Specific resistance at 20° C.	
	Centimeter cube (microhms)	Circular-mil-foot (ohms)
Silver	1.629	9.8
Copper (drawn).	1.724	10.37
Gold	2.44	14.7
Aluminum . . .	2.828	17.02
Carbon (amorphous.)	3.8 to 4.1	. . . .
Tungsten	5.51	33.2
Brass	7.0	42.1
Steel (soft) . . .	15.9	95.8
Nichrome . . .	109.0	660.0

For example, what is the resistance of 1,000 feet of copper wire having a cross-sectional area of 10,400 circular mils (No. 10 wire), the wire temperature being 20° C.?

Solution:

The specific resistance, from table 6-1, is 10.37. Substituting the known values in the preceding equation, the resistance, R, is determined as

$$R = \rho\frac{L}{A} = 10.37 \times \frac{1{,}000}{10{,}400} = 1 \text{ ohm, approximately.}$$

If R, ρ, and A are known, the length may be determined by a simple mathematical transposition. This is of value in many applications. For example, when it is desired to locate a ground in a telephone line, special test equipment is used that operates on the principle that the resistance of a line varies directly with its length. Thus, the distance between the test point and a fault can be computed accurately.

As has been mentioned in preceding chapters, conductance (G) is the reciprocal of resistance. When R is in ohms, the conductance is expressed in mhos. Where resistance is opposition to flow, conductance is the ease with which the current flows. Conductance in mhos is equivalent to the number of amperes flowing in a conductor per volt of applied e.m.f. Expressed in terms of the specific resistance, length, and cross section of a conductor,

$$G = \frac{A}{\rho L}\ .$$

The conductance, G, varies directly as the cross-sectional area, A, and inversely as the specific resistance, ρ, and the length, L. When A is in circular mils, ρ is in ohms per circular-mil-foot, L is in feet, and G is in mhos.

The relative conductance of several substances is given in table 6-2.

Table 6-2.—Relative Conductance.

Substance	Relative conductance (Silver = 100%)
Silver	100
Copper	98
Gold	78
Aluminum	61
Tungsten	32
Zinc	30
Platinum	17
Iron	16
Lead	15
Tin	9
Nickel	7
Mercury	1
Carbon	0.05

WIRE MEASURE

Relation Between Wire Sizes

Wires are manufactured in sizes numbered according to a table known as the American wire gage (AWG). As may be seen in table 6-3, the wire diameters become smaller as the gage numbers become larger. The largest wire size shown in the table is 0000 (read "4 naught"), and the smallest is number 40. Larger and smaller sizes are manufactured but are not commonly used by the Navy. The ratio of the diameter of one gage number to the diameter of the next higher gage number is a constant, 1.123. The cross-sectional area varies as the square of the diameter. Therefore, the ratio of the cross section of one gage number to that of the next higher gage number is the square of 1.123, or 1.261. Because the cube of 1.261 is very nearly 2, the cross-sectional area is approximately halved, or doubled, every three gage numbers. Also because 1.261 raised to the 10th power is very nearly equal to 10, the cross-sectional area is increased or decreased 10 times every 10 gage numbers.

A No. 10 wire has a diameter of approximately 102 mils, a cross-sectional area of approximately 10,400 circular mils, and a resistance of approximately 1 ohm per 1,000 feet. From these facts it is possible to estimate quickly the cross-sectional area and the resistance of any size copper wire without referring directly to a wire table.

For example, to estimate the cross-sectional area and the resistance of 1,000 feet of No. 17 wire, the following reasoning might be employed. A No. 17 wire is 3 sizes removed from a No. 20 wire and therefore has twice the cross-sectional area of a No. 20 wire. A No. 20 wire is 10 sizes removed from a No. 10 wire and therefore has one-tenth the cross section of a No. 10 wire. Therefore, the cross-sectional area of a No. 17 wire is 2 x 0.1 x 10,000 = 2,000 circular mils. Since resistance varies inversely with the cross-sectional area, the resistance of a No. 17 wire is 10 x 1 x 0.5 = 5 ohms per 1,000 feet.

A wire gage is shown in figure 6-3. It will measure wires ranging in size from number 0 to number 36. The wire whose size is to be measured is inserted in the smallest slot that will just accommodate the bare wire. The gage number corresponding to that slot indicates the wire size. The slot has parallel sides and should not be confused with the semicircular opening at the end of the slot. The opening simply permits the free movement of the wire all the way through the slot.

Stranded Wires and Cables

A WIRE is a slender rod or filament of drawn metal. The definition restricts the term to what would ordinarily be understood as "solid wire." The word "slender" is used because the length of a wire is usually large in comparison with the diameter. If a wire is covered with insulation, it is properly called an insulated wire. Although the term "wire" properly refers to the metal, it is generally understood to include the insulation.

A CONDUCTOR is a wire or combination of wires not insulated from one another, suitable for carrying an electric current.

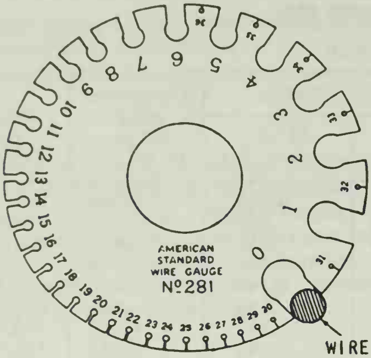
Table 6-3.—Standard annealed solid copper wire.

(American wire gage--B & S)

Gage number	Diameter (mils)	Cross section		Ohms per 1,000 ft.		Ohms per mile 25° C. (=77° F.)	Pounds per 1,000 ft.
		Circular mils	Square inches	25° C. (= 77° F.)	65° C. (= 149° F.)		
0000	460.0	212,000.0	0.166	0.0500	0.0577	0.264	641.0
000	410.0	168,000.0	.132	.0630	.0727	.333	508.0
00	365.0	133,000.0	.105	.0795	.0917	.420	403.0
0	325.0	106,000.0	.0829	.100	.116	.528	319.0
1	289.0	83,700.0	.0657	.126	.146	.665	253.0
2	258.0	66,400.0	.0521	.159	.184	.839	201.0
3	229.0	52,600.0	.0413	.201	.232	1.061	159.0
4	204.0	41,700.0	.0328	.253	.292	1.335	126.0
5	182.0	33,100.0	.0260	.319	.369	1.685	100.0
6	162.0	26,300.0	.0206	.403	.465	2.13	79.5
7	144.0	20,800.0	.0164	.508	.586	2.68	63.0
8	128.0	16,500.0	.0130	.641	.739	3.38	50.0
9	114.0	13,100.0	.0103	.808	.932	4.27	39.6
10	102.0	10,400.0	.00815	1.02	1.18	5.38	31.4
11	91.0	8,230.0	.00647	1.28	1.48	6.75	24.9
12	81.0	6,530.0	.00513	1.62	1.87	8.55	19.8
13	72.0	5,180.0	.00407	2.04	2.36	10.77	15.7
14	64.0	4,110.0	.00323	2.58	2.97	13.62	12.4
15	57.0	3,260.0	.00256	3.25	3.75	17.16	9.86
16	51.0	2,580.0	.00203	4.09	4.73	21.6	7.82
17	45.0	2,050.0	.00161	5.16	5.96	27.2	6.20
18	40.0	1,620.0	.00128	6.51	7.51	34.4	4.92
19	36.0	1,290.0	.00101	8.21	9.48	43.3	3.90
20	32.0	1,020.0	.000802	10.4	11.9	54.9	3.09
21	28.5	810.0	.000636	13.1	15.1	69.1	2.45
22	25.3	642.0	.000505	16.5	19.0	87.1	1.94
23	22.6	509.0	.000400	20.8	24.0	109.8	1.54
24	20.1	404.0	.000317	26.2	30.2	138.3	1.22
25	17.9	320.0	.000252	33.0	38.1	174.1	0.970
26	15.9	254.0	.000200	41.6	48.0	220.0	0.769
27	14.2	202.0	.000158	52.5	60.6	277.0	0.610
28	12.6	160.0	.000126	66.2	76.4	350.0	0.484
29	11.3	127.0	.0000995	83.4	96.3	440.0	0.384
30	10.0	101.0	.0000789	105.0	121.0	554.0	0.304
31	8.9	79.7	.0000626	133.0	153.0	702.0	0.241
32	8.0	63.2	.0000496	167.0	193.0	882.0	0.191
33	7.1	50.1	.0000394	211.0	243.0	1,114.0	0.152
34	6.3	39.8	.0000312	266.0	307.0	1,404.0	0.120
35	5.6	31.5	.0000248	335.0	387.0	1,769.0	0.0954
36	5.0	25.0	.0000196	423.0	488.0	2,230.0	0.0757
37	4.5	19.8	.0000156	533.0	616.0	2,810.0	0.0600
38	4.0	15.7	.0000123	673.0	776.0	3,550.0	0.0476
39	3.5	12.5	.0000098	848.0	979.0	4,480.0	0.0377
40	3.1	9.9	.0000078	1,070.0	1,230.0	5,650.0	0.0299

A STRANDED CONDUCTOR is a conductor composed of a group of wires or of any combination of groups of wires. The wires in a stranded conductor are usually twisted together.

A CABLE is either a stranded conductor (single-conductor cable) or a combination of conductors insulated from one another (multiple-conductor cable). The term cable is a general one, and in practice it is usually applied only to the larger sizes of conductors. A small cable is more often called a stranded wire or cord. Cables may be bare or insulated. The


AMERICAN
STANDARD
WIRE GAUGE
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36
WIRE

Figure 6-3.—Wire gage.

insulated cables may be sheathed (covered) with lead, or protective armor.

Figure 6-4 shows some of the different types of wire and cables used in the Navy.

Conductors are stranded mainly to increase their flexibility. The arrangement of the wire strands in concentric-layer cables is as follows:

The first layer of strands around the center is made up of 6 conductors; the second layer is made up of 12 conductors; the third layer is made up of 18 conductors; and so on. Thus, standard cables are composed of 1, 7, 19, 37, and so forth strands.

The overall flexibility may be increased by further stranding of the individual strands.

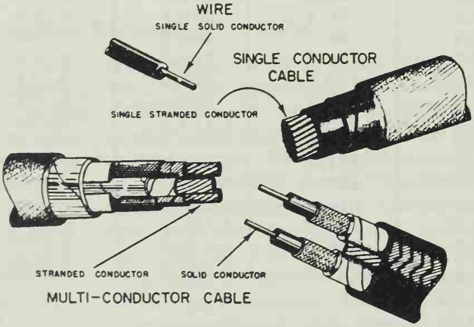
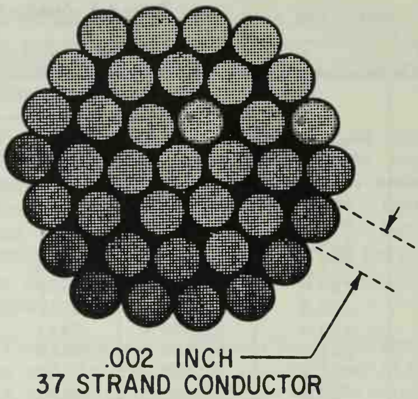

WIRE
SINGLE SOLID CONDUCTOR
SINGLE CONDUCTOR CABLE
SINGLE STRANDED CONDUCTOR
STRANDED CONDUCTOR
SOLID CONDUCTOR
MULTI-CONDUCTOR CABLE

Figure 6-4.—Conductors.

Figure 6-5 shows a typical 37-strand cable. It also shows how the total circular-mil cross-sectional area of a stranded cable is determined.


.002 INCH
37 STRAND CONDUCTOR

DIAMETER OF EACH STRAND = .002 INCH
DIAMETER OF EACH STRAND, MILS = 2 MILS
CIRCULAR MIL AREA OF
EACH STRAND = D^2 = 4 CM
TOTAL CM AREA OF
CONDUCTOR = 4 x 37 = 148 CM

Figure 6-5.—Stranded conductor.

Factors Governing the Selection of Wire Size

Several factors must be considered in selecting the size of wire to be used for transmitting and distributing electric power.

One factor is the allowable power loss (I^2R loss) in the line. This loss represents electrical energy converted into heat. The use of large conductors will reduce the resistance and therefore the I^2R loss. However, large conductors are more expensive initially than small ones; they are heavier and require more substantial supports.

A second factor is the permissible voltage drop (IR drop) in the line. If the source maintains a constant voltage at the input to the line, any variation in the load on the line will cause a variation in line current, and a consequent variation in the IR drop in the line. A wide variation in the IR drop in the line causes poor voltage regulation at the load. The obvious remedy is to reduce either I or R. A reduction in load current lowers the amount of power being transmitted, whereas a reduction in line resistance increases the size and weight of conductors required. A compromise is generally reached whereby the voltage variation at the load is within tolerable limits and the weight of line conductors is not excessive.

A third factor is the current-carrying ability of the line. When current is drawn through the line, heat is generated. The temperature of the line will rise until the heat radiated, or otherwise dissipated, is equal to the heat generated by the passage of current through the line. If the conductor is insulated, the heat generated in the conductor is not so readily removed as it would be if the conductor were not insulated. Thus, to protect the insulation from too much heat, the current through the conductor must be maintained below a certain value. Rubber insulation will begin to deteriorate at relatively low temperatures. Varnished cloth insulation retains its insulating properties at higher temperatures; and other insulation—for example, asbestos or silicon—is effective at still higher temperatures.

Electrical conductors may be installed in locations where the ambient (surrounding) temperature is relatively high; in which case the heat generated by external sources constitutes an appreciable part of the total conductor heating. Due allowance must be made for the influence of external heating on the allowable conductor current and each case has its own specific limitations. The maximum allowable operating temperature of insulated conductors is specified in tables and varies with the type of conductor insulation being used.

Tables have been prepared by the National Board of Fire Underwriters giving the safe current ratings for various sizes and types of conductors covered with various types of insulation. For example, the allowable current-carrying capacities of copper conductors at not over 30° C. (86° F.) room temperature for single conductors in free air are given in table 6-4.

COPPER VS. ALUMINUM CONDUCTORS

Although silver is the best conductor, its cost limits its use to special circuits where a substance with high conductivity is needed.

The two most generally used conductors are copper and aluminum. Each has characteristics that make its use advantageous under certain circumstances. Likewise, each has certain disadvantages.

Copper has a higher conductivity; it is more ductile (can be drawn out), has relatively high tensile strength, and can be easily soldered. It is more expensive and heavier than aluminum.

Although aluminum has only about 60 percent of the conductivity of copper, it is used extensively for high-voltage transmission lines. Its lightness makes possible long spans, and its relatively large diameter for a given conductivity reduces corona—that is, the discharge of electricity from the wire when it has a high potential. The discharge is greater when smaller diameter wire is used than when larger diameter wire is used. However, aluminum conductors are not easily soldered, and aluminum's relatively large size for a given conductance does not permit the economical use of an insulation covering.

A comparison of some of the characteristics of copper and aluminum is given in table 6-5.

TEMPERATURE COEFFICIENT OF RESISTANCE

The resistance of pure metals—such as silver, copper, and aluminum—increases as the temperature increases. However, the resistance of some alloys—such as constantan and manganin—changes very little as the temperature changes. Measuring instruments use these alloys because the resistance of the circuits must remain constant if accurate measurements are to be achieved.

In table 6-1 the resistance of a circular-mil-foot of wire (the specific resistance) is given at a specific temperature, 20° C. in this case. It is necessary to establish a standard temperature because, as has been stated, the resistance of pure metals increase with an increase in temperature; and a true basis of comparison cannot be made unless the resistances of all the substances being compared are measured at the same temperature. The amount of increase in the resistance of a 1-ohm sample of the conductor per degree rise in temperature above 0° C. is called the TEMPERATURE COEFFICIENT OF RESISTANCE. For copper, the value is approximately 0.00427 ohms. For pure metals, the temperature coefficient of resistance ranges between 0.003 and 0.006 ohms.

Thus, a copper wire having a resistance of 50 ohms at an initial temperature of 0° C. will have an increase in resistance of 50 x 0.00427, or 0.214 ohms for the entire length of wire for each degree of temperature rise above 0° C. At 20° C. the increase in resistance is approximately 20 x 0.214, or 4.28 ohms. The total resistance at 20° C. is 50 + 4.28, or 54.28 ohms.

Table 6-4.—Current-carrying capacities (in amperes) of single copper conductors at ambient temperature of below 30° C.

Size	Rubber or thermoplastic	Thermoplastic asbestos, var-cam, or asbestos var-cam	Impregnated asbestos	Asbestos	Slow-burning or weatherproof
0000	300	385	475	510	370
000	260	330	410	430	320
00	225	285	355	370	275
0	195	245	305	325	235
1	165	210	265	280	205
2	140	180	225	240	175
3	120	155	195	210	150
4	105	135	170	180	130
6	80	100	125	135	100
8	55	70	90	100	70
10	40	55	70	75	55
12	25	40	50	55	40
14	20	30	40	45	30

Table 6-5.—Characteristics of copper and aluminum.

Characteristics	Copper	Aluminum
Tensile strength (lb/in^2).	55,000	25,000
Tensile strength for same conductivity (lb).	55,000	40,000
Weight for same conductivity (lb).	100	48
Cross section for same conductivity (C.M.).	100	160
Specific resistance (Ω/mil ft).	10.6	17

CONDUCTOR INSULATION

To be useful and safe, electric current must be forced to flow only where it is needed. It must be "channeled" from the power source to a useful load. In general, current-carrying conductors must not be allowed to come in contact with one another, their supporting hardware, or personnel working near them. To accomplish this, conductors are coated or wrapped with various materials. These materials have such a high resistance that they are, for all practical purposes, nonconductors. They are generally referred to as insulators or insulating material.

Because of the expense of insulation and its stiffening effect, together with the great variety of physical and electrical conditions under which the conductors are operated, only the necessary minimum of insulation is applied for any particular type of cable designed to do a specific job. Therefore there is a wide variety of insulated conductors available to meet the requirements of any job.

Two fundamental properties of insulation materials (for example, rubber, glass, asbestos, and plastic) are insulation resistance and dielectric strength. These are entirely different and distinct properties.

INSULATION RESISTANCE is the resistance to current leakage through and over the surface of insulation materials. Insulation resistance can be measured by means of a megger without damaging the insulation, and information so obtained serves as a useful guide in appraising the general condition of insulation. However, the data obtained in this manner may not give a true picture of the condition of the insulation. Clean-dry insulation having cracks or other faults may show a high value of insulation resistance but would not be suitable for use.

DIELECTRIC STRENGTH is the ability of the insulator to withstand potential difference and is usually expressed in terms of the voltage at which the insulation fails because of the electrostatic stress. Maximum dielectric strength values can be measured by raising the voltage of a TEST SAMPLE until the insulation breaks down.

Rubber

One of the most common types of insulation is rubber. The voltage that may be applied to a rubber-covered pair of conductors (twisted pair) is dependent on the thickness and the quality of the rubber covering. Other factors being equal, the thicker the insulation the higher may be the applied voltage. Figure 6-6 shows two types of rubber-covered wire. One is a single, solid conductor, and the other is a 2-conductor cable in which each stranded conductor is covered with rubber insulation. In each case the rubber serves the same purpose—to confine the current to its conductor.

It may be seen from the enlarged cross-sectional view that a thin coating of tin separates the copper conductor from the rubber insulation. If the thin coating of tin were not used, chemical action would take place and the rubber would become soft and gummy where it makes contact with the copper. When small, solid, or stranded conductors are used, a winding of cotton threads is applied between the conductors and the rubber insulation.

Varnished Cambric

Heat is developed when current flows through a wire, and when a large amount of current flows, considerable heat may be developed. The heat can be dissipated if air is circulated freely around the wire. If a cover of insulation is used, the heat is not removed so readily and the temperature may reach a high value.

Rubber is a good insulator at relatively low voltage as long as the temperature remains low. Too much heat will cause even the best grade of rubber insulation to become brittle

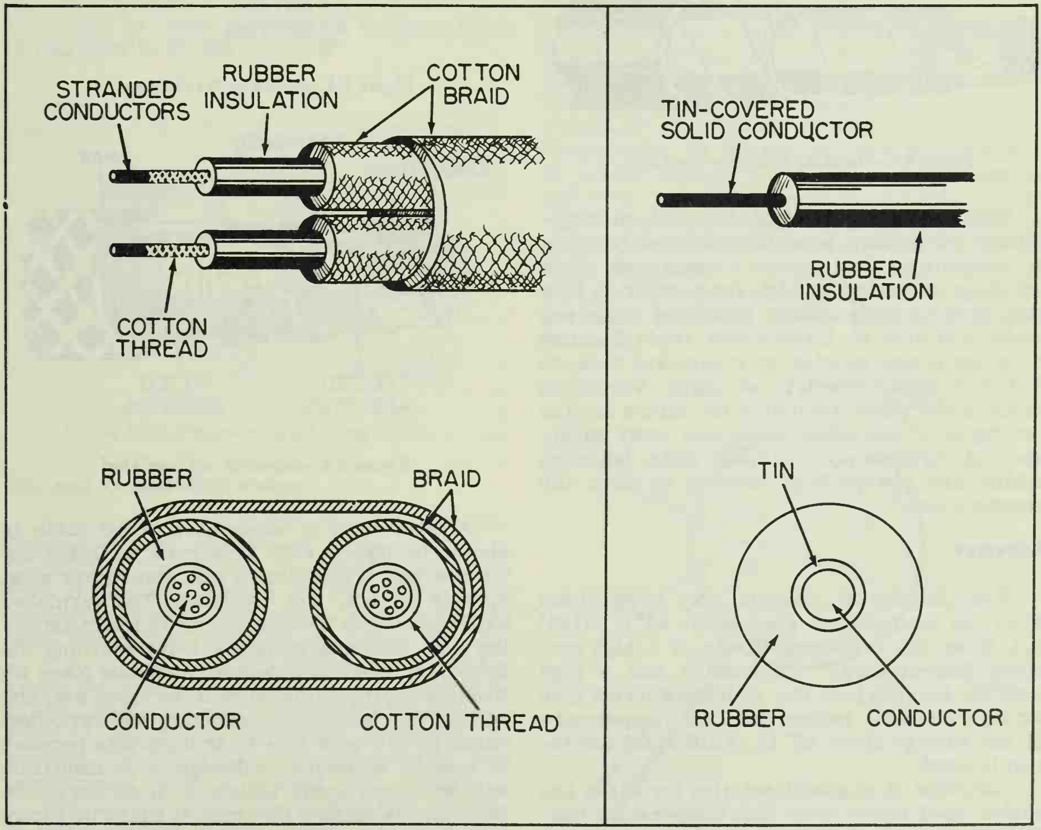

STRANDED CONDUCTORS
RUBBER INSULATION
COTTON BRAID
COTTON THREAD
RUBBER
BRAID
CONDUCTOR
COTTON THREAD
TIN-COVERED SOLID CONDUCTOR
RUBBER INSULATION
TIN
RUBBER
CONDUCTOR

Figure 6-6.—Rubber insulation.

and crack. VARNISHED CAMBRIC insulation will stand much higher temperatures than rubber insulation. Varnished cambric is cotton cloth that has been coated with an insulating varnish. Figure 6-7 shows some of the detail of a cable covered with varnished cambric insulation. The varnished cambric is in tape form and is wound around the conductor in layers. An oily compound is applied between each layer of the tape. This compound prevents water from seeping through the insulation. It also acts as a lubricant between the layers of tape, so they will slide over each other when the cable is bent.

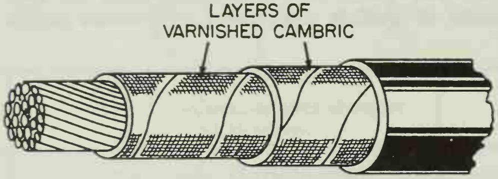


Figure 6-7.—Varnished cambric insulation.

This type of insulation is used on high-voltage conductors associated with switch gear in substations and power houses and other locations subjected to high temperatures. It is also used on high-voltage generator coils and leads, and also on transformer leads because it is unaffected by oils or grease and because it has a high dielectric strength. Varnished cambric and paper insulation for cables are the two types of insulating materials most widely used at voltages above 15,000 volts, but such cables are always lead-covered to keep the moisture out.

Asbestos

Even varnished cambric may break down when the temperature goes above 85° C., (185° F.). When the combined effects of a high ambient (surrounding) temperature and a high internal temperature due to large current flow through the wire makes the total temperature of the wire go above 85° C., ASBESTOS insulation is used.

Asbestos is a good insulation for wires and cables used under very high temperature conditions. It is fire resistant and does not change with age. One type of asbestos-covered wire is shown in figure 6-8. It consists of a stranded copper conductor covered with felted asbestos, which is, in turn, covered with asbestos braid. This type of wire is used in motion-picture projectors, arc lamps, spotlights, heating element leads, and so forth.

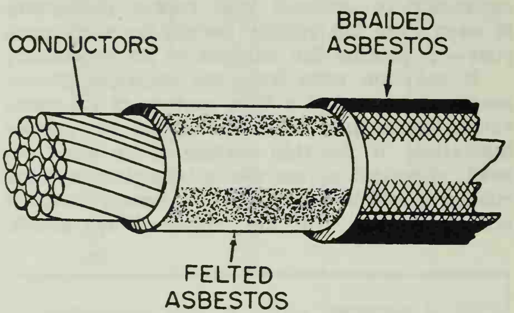


Figure 6-8.—Asbestos insulation.

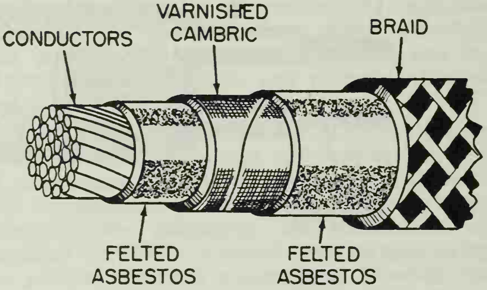


Figure 6-9.—Asbestos and varnished cambric insulation.

Another type of asbestos-covered cable is shown in figure 6-9. It serves as leads for motors and transformers that sometimes must operate in hot, wet locations. The varnished cambric covers the inner layer of felted asbestos and prevents moisture from reaching the innermost layer of asbestos. Asbestos loses its insulating properties when it becomes wet, and will in fact become a conductor. The varnished cambric prevents this from happening because it resists moisture. Although this insulation will withstand some moisture, it should not be used on conductors that may at times be partly immersed in water, unless the insulation is protected with an outer lead sheath.

Paper

Paper has little insulation value alone, but when impregnated with a high grade of mineral oil, it serves as a satisfactory insulation for high-voltage cables. The oil has a high dielectric strength, and tends to prevent breakdown of paper insulation when the paper is thoroughly saturated with it. The thin paper tape is wrapped in many layers around the conductors, and it is then soaked with oil.

The 3-conductor cable shown in figure 6-10 consists of paper insulation on each conductor with a spirally wrapped nonmagnetic metallic tape over the insulation. The space between conductors is filled with a suitable spacer to round out the cable and another nonmagnetic metal tape is used to secure the entire cable, and then a lead sheath is applied over all. This type of cable is used on voltages from 10,000 volts to 35,000 volts.

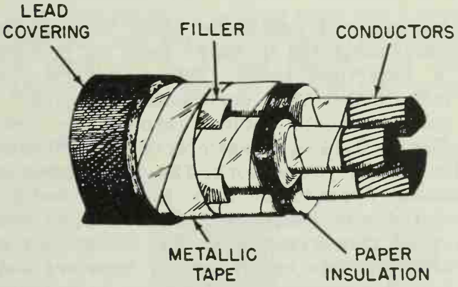


Figure 6-10.—Paper-insulated power cables.

Silk and Cotton

In certain types of circuits—for example, communications circuits—a large number of conductors are needed, perhaps as many as several hundred. Figure 6-11 shows a cable containing many conductors, each insulated from the others by silk and cotton threads.

The use of silk and cotton as insulation keeps the size of the cable small enough to be handled easily. The silk and cotton threads are wrapped around the individual conductors in reverse directions, and the covering is then impregnated with a special wax compound.

Because the insulation in this type of cable is not subjected to high voltage, thin layers of silk and cotton are used.

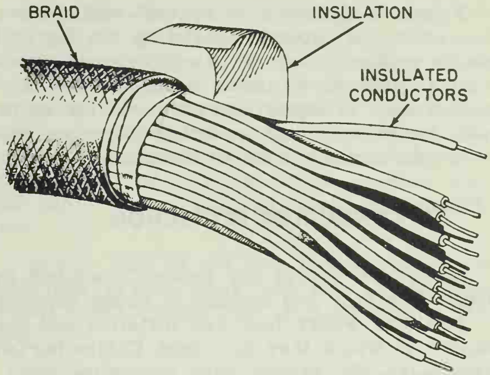


Figure 6-11.—Silk and cotton insulation.

Enamel

The wire used on the coils of meters, relays, small transformers, and so forth, is called MAGNET WIRE. This wire is insulated with an enamel coating. The enamel is a synthetic compound of cellulose acetate (wood pulp and magnesium). In the manufacture, the bare wire is passed through a solution of the hot enamel and then cooled. This process is repeated until the wire acquires from 6 to 10 coatings. Enamel has a higher dielectric strength than rubber for equal thickness. It is not practical for large wires because of the expense and because the insulation is readily fractured when large wires are bent.

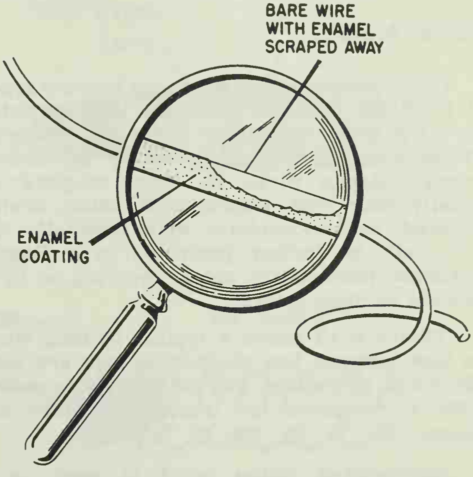

BARE WIRE WITH ENAMEL SCRAPED AWAY
ENAMEL COATING

Figure 6-12.—Enamel insulation.

Figure 6-12 shows an enamel-coated wire. Enamel is the thinnest insulating coating that can be applied to wires. Hence, enamel-insulated magnet wire makes smaller coils. Enameled wire is sometimes covered with one or more layers of cotton covering to protect the enamel from nicks, cuts, or abrasions.

CONDUCTOR PROTECTION

Wires and cables are generally subject to abuse. The type and amount of abuse depends on how and where they are installed and the manner in which they are used. Cables buried directly in the ground must resist moisture, chemical action, and abrasion. Wires installed in buildings must be protected against mechanical injury and overloading. Wires strung on crossarms on poles are kept far enough apart so that they do not touch; but snow, ice, and strong winds necessitate the use of conductors having high tensile strength and substantial supporting frame structures.

Generally, except for overload transmission lines, wires or cables are protected by some form of covering. The covering may be some type of insulator like rubber or plastic. Over this an outer covering of fibrous braid may be applied. If conditions require, a metallic outer covering may be used. The type of outer covering used depends on how and where the wire or cable is to be used.

Fibrous Braid

Cotton, linen, silk, rayon, and jute are types of FIBROUS BRAIDS. They are used for outer covering under conditions where the wires or cables are not exposed to heavy mechanical injury. Interior wiring for lights or power is usually done with impregnated cotton, braid-covered, rubber-insulated wire. Generally, the wire will be further protected by a flame-resistant nonmetallic outer covering or by a flexible or rigid conduit.

Figure 6-13 shows a typical building wire. In this instance two braid coverings are used for extra protection. The outer braid is soaked with a compound that resists moisture and flame.

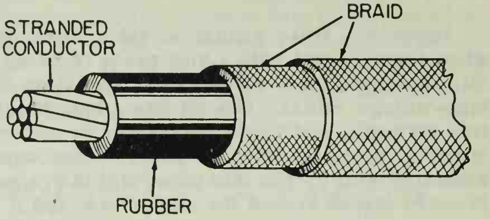


Figure 6-13.—Fibrous braid covering.

Impregnated cotton braid is used as a covering for outdoor overhead conductors to afford protection against abrasion. For example, the service wires from the transformer secondary mains to the service entrance and also the high-voltage primary mains to the transformer are protected in this manner.

Lead Sheath

Subway-type cables or wires that are continually subjected to water must be protected by a watertight cover. This watertight cover is made either of a continuous lead jacket or a rubber sheath molded around the cable.

Figure 6-14 is an example of a lead-sheathed cable used in power work. The cable shown is a stranded 3-conductor type. Each conductor is insulated with rubber and then wrapped with a layer of rubberized tape. The conductors are twisted together and fillers or rope are added to form a rounded core. Over this is wrapped a second layer of tape called the SERVING, and finally the lead sheath is molded around the cable.

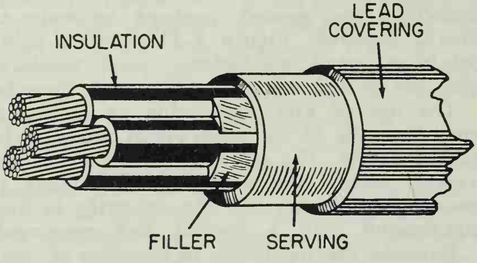


Figure 6-14.—Lead sheathed cable.

Metallic Armor

Metallic armor provides a tough protective covering for wires or cables. The type, thickness, and kind of metal used to make the armor depend on the use of the conductors, the circumstances under which the conductors are to be used, and on the amount of rough treatment that is to be expected.

Four types of metallic armor for cables are shown in figure 6-15.

Wire braid armor is used wherever light, flexible protection is needed. This type of armor is used almost exclusively aboard ship. The individual wires that are woven together to form the metal braid may be made of steel, copper, bronze, or aluminum. Besides mechanical protection, the wire braid also presents a static shield. This is important in radio work aboard ship to prevent interference from stray fields.

When cables are buried directly in the ground, they might be injured from two sources —moisture, and abrasion. They are protected from moisture by a lead sheath, and from abrasion by steel tape or interlocking armor covers. The steel tape covering, as shown in figure 6-15, is wrapped around the cable and then covered with a serving of jute. It is known as Parkway cable. The interlocking armor covering can withstand impacts better than steel tape. Interlocking armor has other uses besides underground work. In wiring the interior of buildings, interlocking armor-covered wire (BX cable) without the lead sheath is frequently used.

Armor wire is the best type of covering to withstand severe wear and tear. Underwater leaded cable usually has an outer armor wire cover.

All wires and cables do not have the same type of protective covering. Some coverings are designed to withstand moisture, others to withstand mechanical strain, and so forth. A cable may have a combination of each type, each doing its own job.

CONDUCTOR SPLICES AND TERMINAL CONNECTIONS

Conductor splices and connections are an essential part of any electric circuit. When

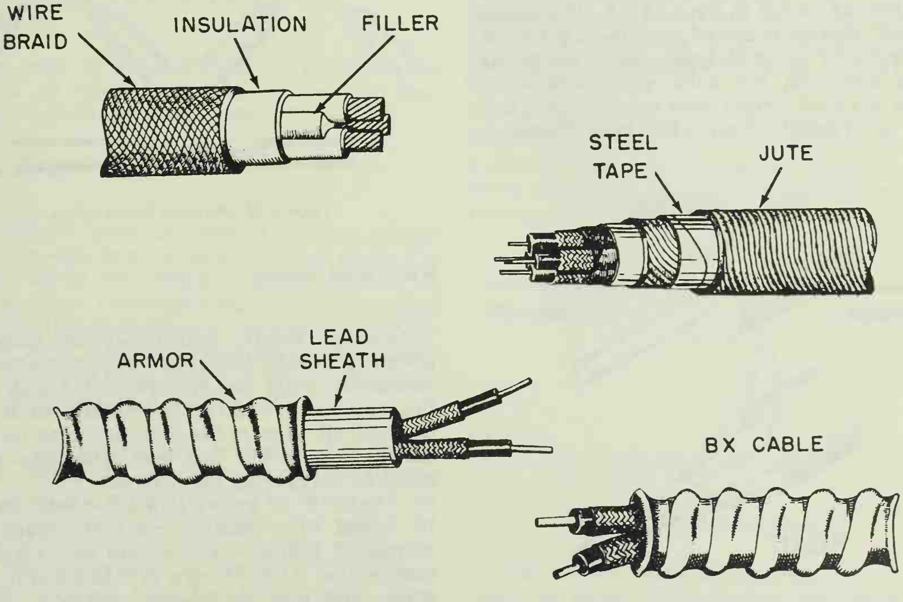


Figure 6-15.—Metallic armor.

conductors join each other, or connect to a load, splices or terminals must be used. It is important that they be properly made, since any electric circuit is only as good as its weakest link. The basic requirement of any splice or connection is that it be both mechanically and electrically as strong as the conductor or device with which it is used. High-quality workmanship and materials must be employed to insure lasting electrical contact, physical strength, and insulation (if required). The most common methods of making splices and connections in electric cables will now be discussed.

Preparing Conductors for Splices and Terminals

The first step in making a splice is preparing the wires or conductor. Insulation must be removed from the end of the conductor and the exposed metal cleaned. In removing the insulation from the wire, a sharp knife is used in much the same manner as in sharpening a pencil. That is, the knife blade is moved at a small angle with the wire to avoid "nicking" the wire. This produces a taper on the cut insulation, as shown in figure 6-16. The insulation may also be removed by using a plier-like hand-operated cable stripper. After the insulation is removed, the bare wire ends should then be scraped bright with the back of a knife blade or rubbed clean with fine sandpaper.

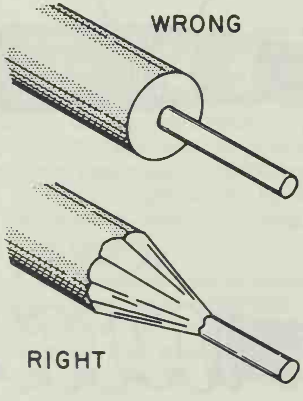


Figure 6-16.—Removing insulation from a wire.

Western Union Splice

Small, solid conductors may be joined together by a simple connection known as the WESTERN UNION SPLICE. In most instances the wires may be twisted together with the fingers and the ends clamped into position with a pair of pliers.

Figure 6-17 shows the steps in making a Western Union splice. First, the wires are prepared for splicing by removing sufficient insulation and cleaning the conductor. Next, the wires are brought to a crossed position and a long twist or bend is made in each wire. Then one of the wire ends is wrapped four of five times around the straight portion of the wire. The other end wire is wrapped in a similar manner. Finally, the ends of the wires should be pressed down as close as possible to the straight portion of the wire. This prevents the sharp ends from puncturing the tape covering that is wrapped over the splice.

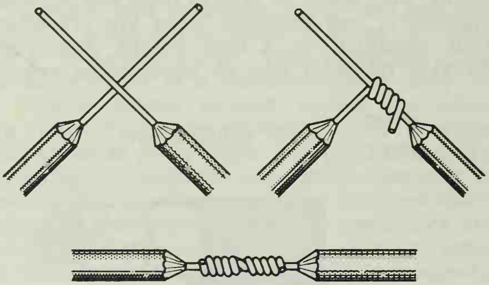


Figure 6-17.—Western Union splice.

Staggered Splice

Joining small, multiconductor cables together presents somewhat of a problem. Each conductor must be spliced and taped; and if the splices are directly opposite each other, the overall size of the joint becomes large and bulky. A smoother and less bulky joint may be made by staggering the splices.

Figure 6-18 shows how a 2-conductor cable is joined to a similar cable by means of the staggered splice. Care should be exercised to ensure that a short wire is connected to a long wire, and that the sharp ends are clamped firmly down on the conductor.

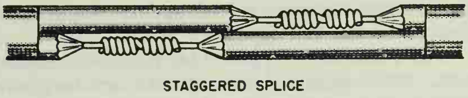


Figure 6-18.–Staggered splice.

Rattail Joint

Wiring that is installed in buildings is usually placed inside long lengths of steel pipe (conduit). Whenever branch circuits are required, junction or pull boxes are inserted in the conduit. One type of splice that is used for branch circuits is the rattail joint shown in figure 6-19.

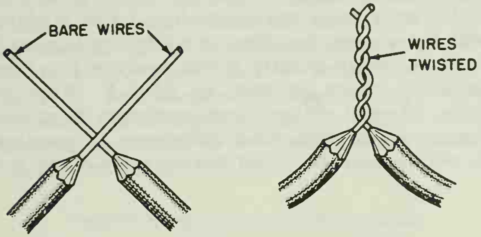


Figure 6-19.–Rattail joint.

The ends of the conductors to be joined are stripped of insulation. The wires are then twisted to form the rattail effect.

Fixture Joint

A fixture joint is used to connect a light fixture to the branch circuit of an electrical system where the fixture wire is smaller in diameter than the branch wire. Like the rattail joint, it will not stand much mechanical strain.

The first step is to remove the insulation from the wires to be joined. Figure 6-20 shows the steps in making a fixture joint.

After the wires are prepared, the fixture wire is wrapped a few times around the branch wire, as shown in the figure. The wires are not twisted, as in the rattail joint. The end of the branch wire is then bent over the completed turns. The remainder of the bare fixture wire is then wrapped over the bent branch wire. Soldering and taping completes the job.

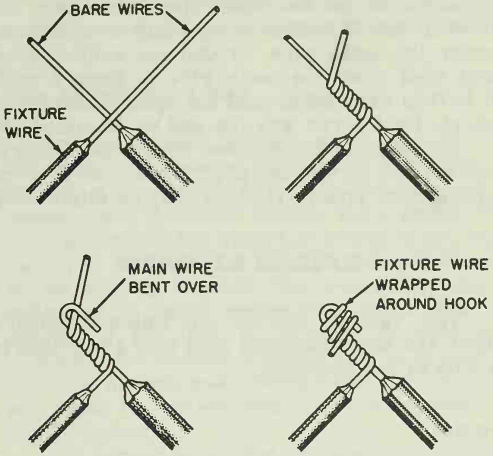


Figure 6-20.–Fixture joint.

Knotted Tap Joint

All of the splices considered up to this point are known as BUTTED splices. Each was made by joining the FREE ends of the conductors together. Sometimes, however, it is necessary to join a conductor to a CONTINUOUS wire, and such a junction is called a TAP joint.

The main wire, to which the branch wire is to be tapped, has about one inch of insulation removed. The branch wire is stripped of about three inches of insulation. The steps in making the tap are shown in figure 6-21.

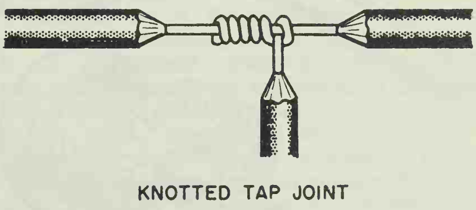


Figure 6-21.–Knotted tap joint.

The branch wire is crossed over the main wire, as shown in the figure, with about three-fourths of the bare portion of the branch wire extending above the main wire. The end of the branch wire is bent over the main wire, brought under the main wire, around the branch wire, and then over the main wire to form a knot. It is then wrapped around the main conductor in short, tight turns and the end is trimmed off.

The knotted tap is used where the splice is subject to strain or slip. When there is no mechanical strain, the knot may be eliminated.

SOLDERING EQUIPMENT

The various splices and joints commonly used are not completed until they are properly soldered and insulated.

Solder

Solder is a metallic alloy with a low melting point; it is used to join metallic surfaces. Solder used in electrical work comes in two forms —solid solder bars, and the rosin core type, resembling wire wound on spools. Figure 6-22 illustrates the two types.

The rosin core type solder is most commonly used. The rosin core of the solder, when melted, flows on the surfaces of the splice or joint, preventing their contact with air and thus preventing oxidation. Without oxidation, the solder and surfaces will cohere strongly.

Soldering Iron

The soldering iron is a handtool that is used to heat the wire splice or joint to a temperature that will cause the solder to melt and flow freely over the splice or joint. Electric soldering irons are rated in watts, from 25 to 500. The size of the conductors being soldered will determine the size of soldering iron to be used. All high quality irons operate in a temperature range of 500° to 600° F. Even the little 25-watt midget iron produces this temperature. The important difference in iron sizes is not temperature, but the capacity of the iron

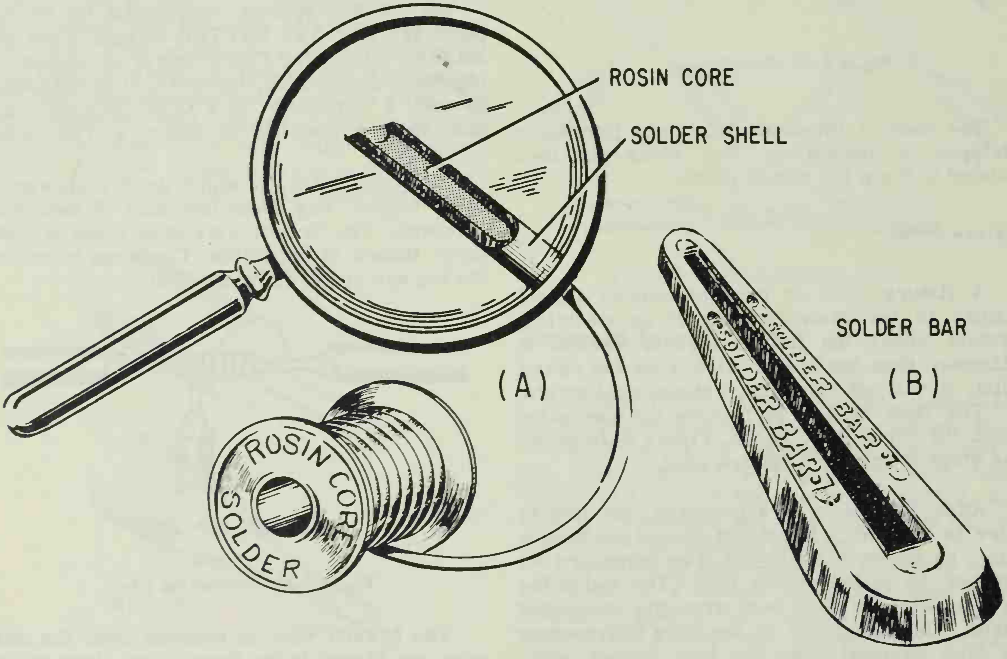


Figure 6-22.—Solder: (A) Rosin core; (B) solid bars.

to generate and maintain a satisfactory soldering temperature while giving up heat to the joint to be soldered.

Some irons have built-in thermostats. Others are provided with thermostatically controlled stands. One type of iron is equipped with several different tips that range from 1/4 inch to 1/2 inch is size (diameter) and are of various shapes. This feature makes the iron adaptable to a variety of jobs. Figure 6-23 shows several different type soldering irons.

ELECTRIC HEATING ELEMENT SOLDERING IRON

Figure 6-23 (A) shows three common sizes of the electric heating element soldering iron. This is the most commonly used type iron. A cylindrical electric heating element is mounted in its body. About half of the copper tip is inserted and secured within the cylindrical element, obtaining heat by physical contact. Heat is conducted to the protruding half, to be used in melting solder.

INDUCTION-TYPE SOLDERING IRON

This soldering iron (most often referred to as "soldering gun") is shown in figure 6-23 (B). It contains a stepdown transformer in its body. The transformer secondary output current flows through the tip, causing it to heat. The tip heats only when the trigger is depressed, and then very rapidly. This type iron affords easy access to cramped quarters, because of its small tip. It usually has a small light which is focused on the tip working area. The soldering tip is replaceable.

ELECTRIC RESISTANCE SOLDERING IRON

This iron is shown in figure 6-23 (C). When the contact jaws are clamped on the work, current flows between the jaws through the work. The contact resistance causes heating, thus melting the solder.

TORCH-HEATED SOLDERING IRON

As shown in figure 6-23 (D), this type iron is heated directly by a blowtorch or other heat source. It is then held against the soldering work to transfer its heat. After cooling to an unusable temperature, it is reheated. This iron is usually used where electric power is not available and an open flame is permissible.

Care of Soldering Iron

Soldering irons require more care in both use and maintenance than most handtools. A typical electric iron has a heating element, a power cord, a wooden handle, and a copper tip.

The copper tip generally requires the most care and maintenance. Also, to prevent damage to the heating element, the iron should not be subjected to heavy mechanical abuse. For instance, if the iron is dropped, or used as a hammer, the heating element may be broken or shorted. Always make certain that the cord does not come in contact with the iron tip, where it can be burned.

The copper tip should be removed occasionally to permit cleaning away the oxide scale which forms between the tip and metal housing. Removal of this oxide increases the heating efficiency of the iron.

Before a soldering iron can be used for soldering, the pointed end of the copper tip must be tinned. Unless the tip is tinned the iron will not readily transfer heat from the copper tip to the connection to be soldered. Tinning the end of the copper means covering it with a thin coating of solder. After heating, all of the tip except the tinned portion becomes covered with an oxide film. This film does not readily conduct heat. Only the tinned portion of the tip will give off enough heat to melt solder readily. An iron which needs tinning does not produce satisfactory results when making solder connections. After an iron has been used for a period of time, the solder on the tip burns off and the iron needs retinning.

The action of the heat and solder causes pitting and corroding of the tip. Consequently, it not only needs retinning occasionally, but also needs occasional reshaping. Tips usually either have a 4-sided taper point or a 2-sided chisel point. Regardless of the tip size or shape, the same tinning procedure is used.

To reshape the tip, first remove it from the iron, either by unscrewing it from the housing or loosening a setscrew, depending on the type of iron. Place the tip in a vise with the point in such a position that the side to be tinned can be filed. Do not tighten the vise too tightly, as the copper tip is soft and bends easily. Using flat strokes, file the sides of the point until all of

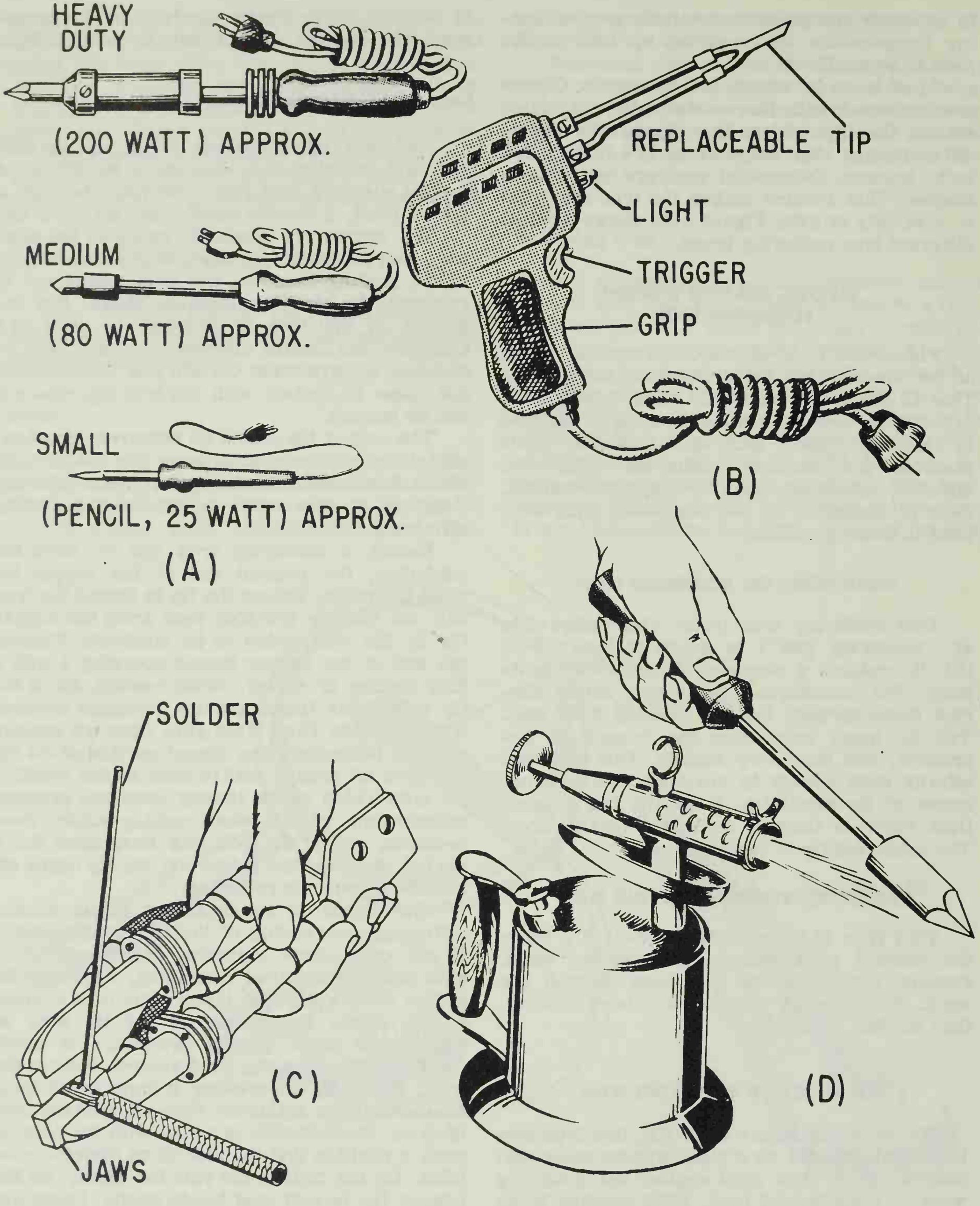

HEAVY DUTY
(200 WATT) APPROX.
MEDIUM
(80 WATT) APPROX.
SMALL
(PENCIL, 25 WATT) APPROX.
(A)
REPLACEABLE TIP
LIGHT
TRIGGER
GRIP
(B)
SOLDER
JAWS
(C)
(D)

Figure 6-23.—Soldering irons.

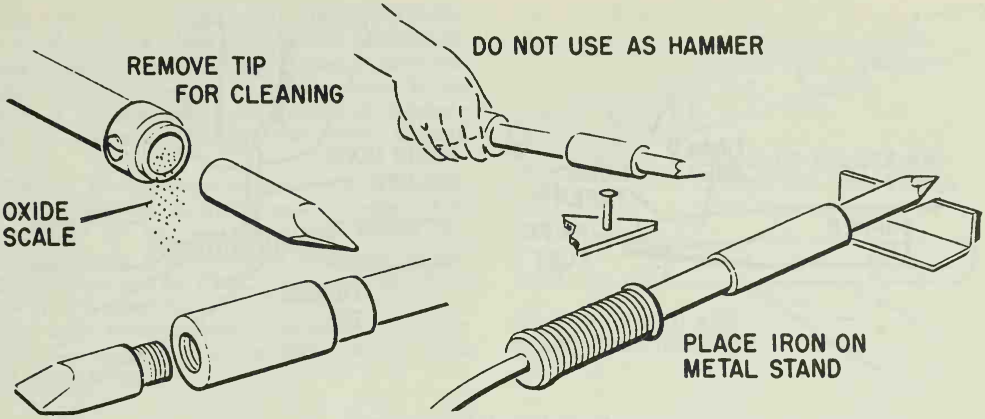


Figure 6-24.—Caring for the soldering iron.

the pits, oxide, and old tinning are removed. Always file the tip to the original taper, making certain that you do not round off the sides of the point.

Replace the filed tip in the iron housing. Holding the iron with the tip upward, plug the cord into a power outlet. As the iron heats, touch rosin core solder to the cleaned sides of the tip at intervals until the iron first begins to melt the solder. Then quickly melt solder onto all of the cleaned portion of the tip, applying as much solder as will melt onto each side. With a dry cloth or piece of steel wool, lightly brush the excess solder from the tinned sides of the tip. The iron is now ready to use for soldering. Heated irons, when not in actual use, should be placed on a metal iron rest or some other appropriate holder.

To solder an electrical connection, the tinned portion of the iron tip is held flat against the connection, as shown in figure 6-25. Touch solder to the connection until the entire connection is covered with molten solder. Remove the solder, but continue to apply heat for a moment; then remove the iron and allow the solder to harden. The solder should always be melted by the heated wire and not by the iron. Melting the solder onto the iron and then transferring it to the connection often results in a cold solder joint, with the solder not actually holding to the wire or connection. Only enough solder to fill all crevices and spaces in the joint should be used.

TAPING A SPLICE

The final step in completing a splice or joint is the placing of insulation over the bare wire. The insulation should be of the same basic substance as the original insulation. Usually a rubber splicing compound is used.

Rubber Tape

Latex (rubber) tape is a splicing compound. It is used where the original insulation was rubber. The tape is applied to the splice with a light tension so that each layer presses tightly against the one underneath it. This pressure causes the rubber tape to blend into a solid mass. When the application is completed, an insulation similar to the original has been restored.

Between each layer of latex tape, when it is in roll form, there is a layer of paper or treated cloth. This layer prevents the latex from fusing while still on the roll. The paper or cloth is peeled off and discarded before the tape is applied to the splice.

Figure 6-26 shows the correct way to cover a splice with rubber insulation. The rubber splicing tape should be applied smoothly and under tension so that there will be no air spaces between the layers. In putting on the first layer, start near the middle of the joint instead of the end. The diameter of the completed insulated joint should be somewhat greater that

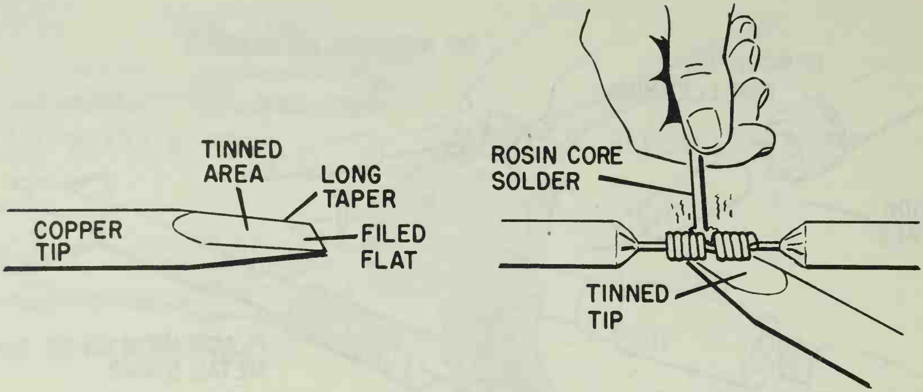


Figure 6-25.–Soldering a splice.

the overall diameter of the original cable, including the insulation.

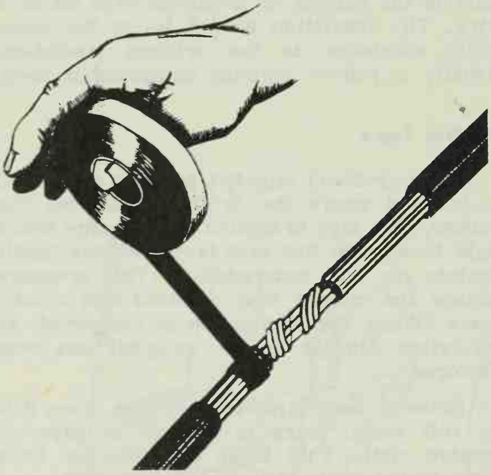


Figure 6-26.–Applying rubber tape.

Friction Tape

Putting rubber tape over the splice means that the insulation has been restored to a great degree. It is also necessary to restore the protective covering. Friction tape is used for this purpose; it also affords a minor degree of electrical insulation.

Friction tape is a cotton cloth that has been treated with a sticky rubber compound. It comes in rolls similar to rubber tape except that no paper or cloth separator is used. Friction tape is applied like rubber tape; however, it does not stretch.

The friction tape should be started slightly back on the original braid covering. Wind the tape so that each turn overlaps the one before it; and extend the tape over onto the braid covering at the other end of the splice. From this point a second layer is wound back along the splice until the original starting point is reached. Cutting the tape and firmly pressing down the end complete the job. When proper care is taken, the splice can take as much abuse as the rest of the wire.

Weatherproof wire has no rubber insulation, just a braid covering. In that case, no rubber tape is necessary, only friction tape need be used.

Plastic Electrical Tape

Plastic electrical tape has come into wide use in recent years. It has certain advantages over rubber and friction tape. For example, it will withstand higher voltages for a given thickness. Single thin layers of certain commercially available plastic tape will stand several thousand volts without breaking down. However, to provide an extra margin of safety several layers are usually wound over the splice. Because the tape is very thin, the extra layers add only a very small amount of bulk; but at the same time the added protection, normally furnished by friction tape, is provided by the additional layers of plastic tape. In the choice of plastic tape, the factor of expense must be balanced against the other factors involved.

Plastic electric tape normally has a certain amount of stretch so that it easily conforms to the contour of the splice without adding unnecessary bulk. The lack of bulkiness is especially important in some junction boxes where space is at a premium.

For high temperatures—for example, above 175° F.—a special type of tape backed with glass cloth is used.

SOLDER CONNECTORS

In some cases, splices and joints cannot readily be made by twisting and soldering conductors. For instance, it would be quite difficult to twist conductors together neatly if each consisted of many small strands. Stranded conductors are usually spliced by using special hardware designed for that purpose. Some of these devices use solder, while others do not.

Solder Splicers

The solder-type splicer is essentially a short piece of metal tube. Its inside diameter is just large enough to allow the tip of a stranded conductor to be inserted in either end, after the conductor tip has been stripped of insulation. This type of splicer is shown in figure 6-27.

The splicer is first heated and filled with solder. While still molten, the solder is then poured out, leaving the inner surfaces tinned. When the conductor tips are stripped, the length of exposed strands should be long enough so that the insulation butts against the splicer when the conductors are tinned and fully inserted. (See fig. 6-27 (B).) When heat is applied to the connection and the solder melts, excess solder will be squeezed out through the vents. This must be cleaned away. After the splice has cooled, insulating material must be wrapped or tied over the joint.

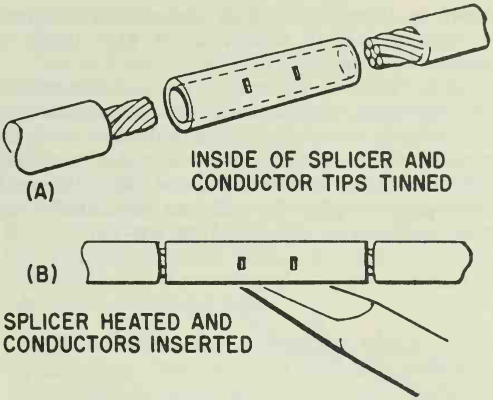

(A)
INSIDE OF SPLICER AND CONDUCTOR TIPS TINNED
(B)
SPLICER HEATED AND CONDUCTORS INSERTED

Figure 6-27.—Steps in using solder splicer.

Solder Terminal Lugs

In addition to being joined or spliced to one another, conducts are often connected to other objects, such as motors and switches. Since this is where a length of conductor ends (terminates), such connections are referred to as terminal points. In some cases, it is allowable to bend the end of the conductor into a small "eye" and put it around a terminal binding post. Where a mounting screw is used, the screw is passed through the eye. The conductor tip which forms the eye should be bent as

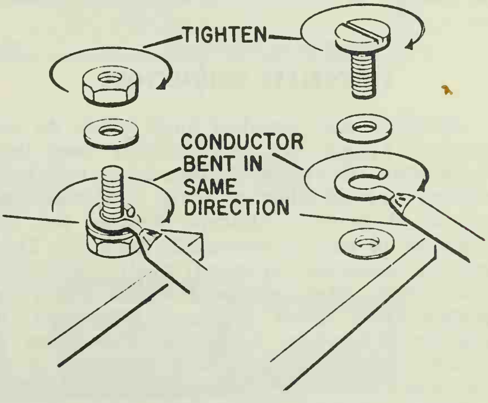


Figure 6-28.—Conductor terminal connection.

shown in figure 6-28. Note that when the screw or binding nut is tightened, it also tends to tighten the conductor eye.

This method of connection is sometimes not desirable. When design requirements are more rigid, terminal connections are made by using special hardware devices called terminal lugs. There are terminal lugs of many different sizes and shapes, but all are essentially the same as the type shown in figure 6-29.

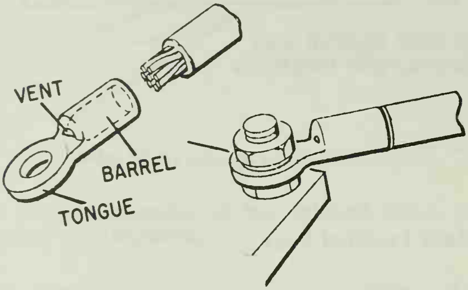


Figure 6-29.—Solder-type terminal lug.

Each type of lug has a barrel (sleeve) which is wedged, crimped, or soldered to its conductor. There is also a tongue with a hold or slot in it to receive the terminal post or screw. When mounting a solder-type terminal lug to a conductor, first tin the inside of the barrel. The conductor tip is stripped and also tinned, then inserted in the preheated lug. When mounted, the conductor insulation should butt against the lug barrel, so that there is no exposed conductor.

SOLDERLESS CONNECTORS

Splicers and terminal lugs which do not require solder are more widely used than those which do require solder. Solderless connectors are attached to their conductors by means of several different devices, but the principle of each is essentially the same. They are all squeezed (crimped) tightly onto their conductors. They afford adequate electrical contact, plus great mechanical strength. In addition, solderless connectors are easier to mount correctly because they are free from the most common problems of solder connector mounting; namely, cold solder joints, burned insulation, and so forth.

Solderless connectors are made in a great variety of sizes and shapes, and for many different purposes. Only a few are discussed here.

Solderless Splicers

Three of the most common type solderless splicers, classified according to their methods of mounting, are the split-sleeve, split-tapered-sleeve, and crimp-on splicers.

SPLIT-SLEEVE SPLICER

A split-sleeve splicer is shown in figure 6-30. To connect this splicer to its conductor, the stripped conductor tip is first inserted between the split-sleeve jaws. Using a tool designed for that purpose, the slide ring is forced toward the end of the sleeve. The sleeve jaws are closed tightly on the conductor, and the slide ring holds them securely.

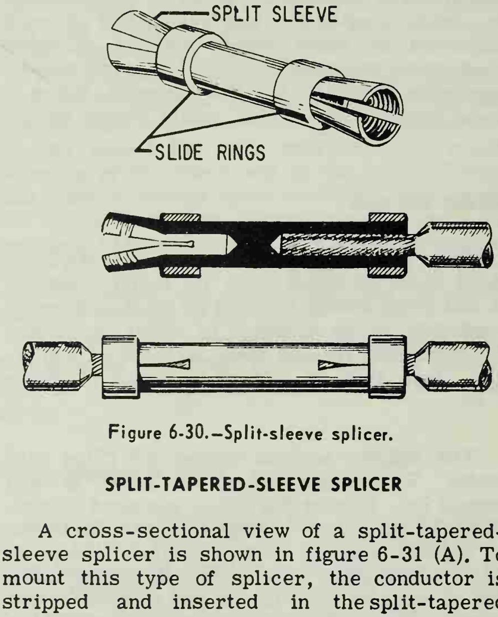


Figure 6-30.—Split-sleeve splicer.

SPLIT-TAPERED-SLEEVE SPLICER

A cross-sectional view of a split-tapered-sleeve splicer is shown in figure 6-31 (A). To mount this type of splicer, the conductor is stripped and inserted in the split-tapered sleeve. The threaded sleeve is turned or screwed into the tapered bore of the body. As the sleeve is turned in, the split segments are squeezed tightly around the conductor by the narrowing bore. The finished splice (fig. 6-31 (B)), must be covered with insulation.

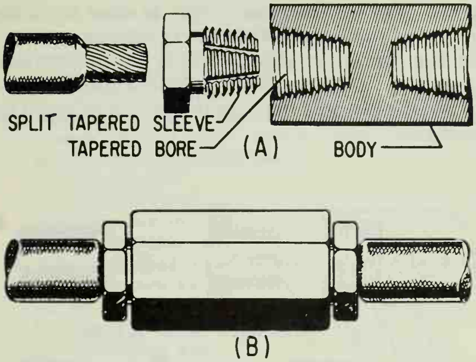


Figure 6-31.—Split-tapered-sleeve splice.

CRIMP-ON SPLICER

The crimp-on splicer (fig. 6-32) is the simplest of the splicers discussed. The type shown is preinsulated, though uninsulated types are manufactured. These splicers are mounted with a special plier-like hand-crimping tool designed for that purpose. The stripped conductor tips are inserted in the splicer, which is then squeezed tightly closed. The insulating sleeve grips the outer insulated conductor, and the metallic internal splicer grips the bare conductor strands.

Solderless Terminal Lugs

Solderless terminal lugs are used more widely than solder terminal lugs. They afford adequate electrical contact, plus great mechanical strength. In addition, solderless lugs are easier to attach correctly, because they are free from the most common problems of solder terminal lugs; namely, cold solder joints, burned insulation, and so forth. There are many sizes and shapes of these lugs, each intended for a different type of service of conductor size. Only a few are discussed here.

These are classified according to their method of mounting. They are the split-tapered-sleeve (wedge-type), split-tapered-sleeve (threaded-type), and crimp-on.

SPLIT-TAPERED-SLEEVE TERMINAL LUG (WEDGE)

This type lug is shown in figure 6-33. It is commonly referred to as a "wedge-on," because of the manner in which it is secured to a conductor. The stripped conductor is inserted through the hole in the split sleeve. When the sleeve is forced or "wedged" down into the barrel, its tapered segments are squeezed tightly around the conductor.

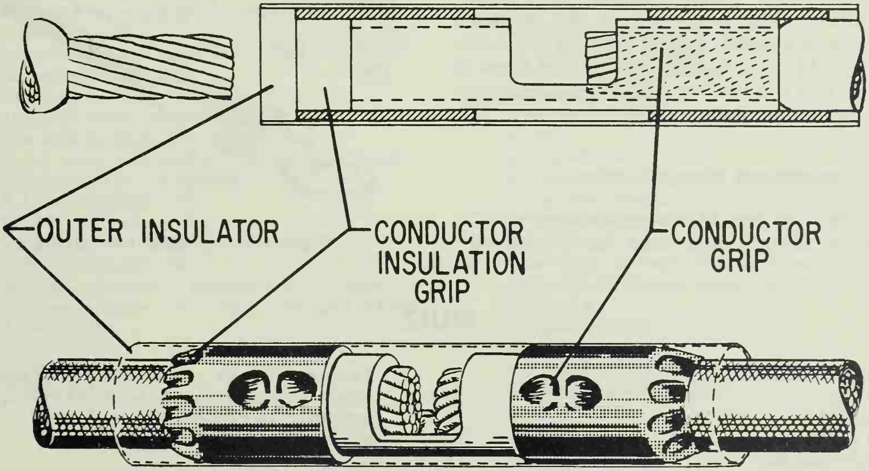


Figure 6-32.—Crimp-on splicer.

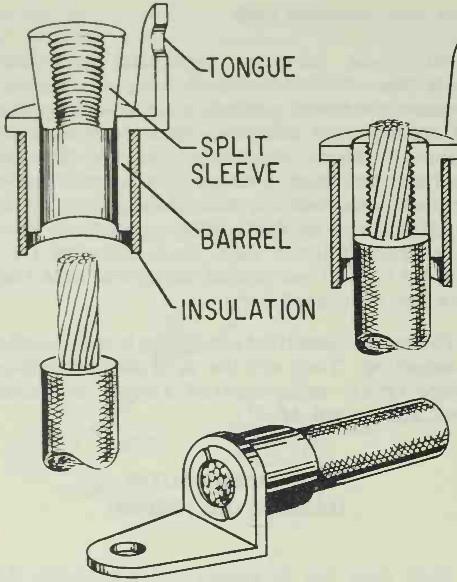

TONGUE
SPLIT SLEEVE
BARREL
INSULATION

Figure 6-33.—Split-tapered-sleeve terminal lug (wedge type).

SPLIT-TAPERED-SLEEVE TERMINAL LUG (THREADED)

This lug (fig. 6-34) is attached to a conductor in exactly the same manner as a split-sleeve splicer. The segments of the threaded split sleeve squeezes tightly around the conductor as it is turned into the tapered bore of the barrel. For this reason, the lug is commonly referred to as a "screw-wedge."

CRIMP-ON TERMINAL LUG

The crimp-on lug is shown in figure 6-35. This lug is simply squeezed or "crimped" tightly onto a conductor. This is done by using the same tool used with the crimp-on splicer. The lug shown is preinsulated, but uninsulated types are manufactured. When mounted, both the conductor and its insulation are gripped by the lug.

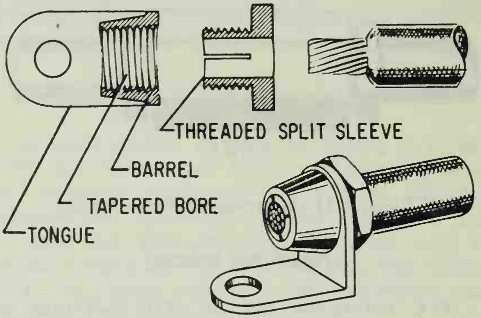

THREADED SPLIT SLEEVE
BARREL
TAPERED BORE
TONGUE

Figure 6-34.—Split-tapered-sleeve terminal lug (threaded).

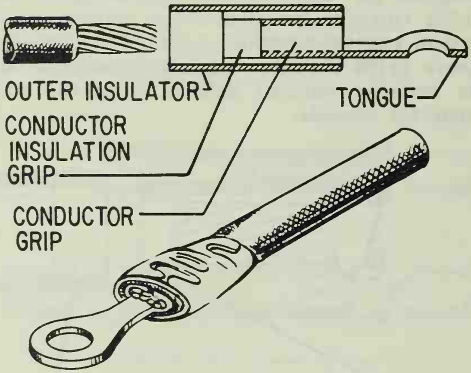

OUTER INSULATOR
TONGUE
CONDUCTOR INSULATION GRIP
CONDUCTOR GRIP

Figure 6-35.—Crimp-on terminal lug.

QUIZ

1. A mil is what part of an inch?
   a. 1/10
   b. 1/100
   c. 1/1000
   d. 1/1,000,000

2. The discharge (electrical leakage) that might occur from a wire carrying a high potential is called
   a. arcing
   b. sparking
   c. static discharge
   d. corona

3. Bare wire ends are spliced by the
   a. western union method
   b. rat-tail joint method
   c. fixture joint method
   d. all of the above
4. What is a unit conductor called that has a length of one foot and a cross-sectional area of one circular mil?
   a. Square mil
   b. Circular mil
   c. Circular mil foot
   d. Square mil foot
5. The induction-type soldering iron is commonly known as the
   a. soldering copper
   b. pencil iron
   c. soldering gun
   d. resistance gun
6. All good quality soldering irons operate at what temperature?
   a. 400 - 500° F.
   b. 500 - 600° F.
   c. 600 - 700° F.
   d. 300 - 600° F.
7. A No. 12 wire has a diameter of 80.81 mils. What is the area in circular mils?
   a. 6,530 cm.
   b. 5,630 cm.
   c. 4,530 cm.
   d. 3,560 cm.
8. Dielectric strength is the
   a. opposite of potential difference
   b. ability of a conductor to carry large amounts of current
   c. ability of an insulator to withstand a potential difference
   d. strength of a magnetic field
9. To readily transfer the heat from the soldering iron tip, it first should be
   a. tinned with solder
   b. allowed to form an oxide film
   c. cleaned with carbon tet
   d. allowed to heat for 25 minutes
10. A No. 12 wire has a diameter of 80.81 mils. What is the area in square mils?
   a. 2,516.8 square mils
   b. 5,128.6 square mils
   c. 6,530 square mils
   d. 8,512.6 square mils
11. Varnished cambric insulation is used to cover conductors carrying voltages above
   a. 1,000 volts
   b. 1,500 volts
   c. 15,000 volts
   d. 5,000 volts
12. The solder splicer is used to
   a. prevent the waste of rosin core solder
   b. connect together small lengths of solder
   c. connect two conductors together
   d. none of the above
13. The conductance of a conductor is the ease with which current will flow through it. It is measured in
   a. ohms
   b. mhos
   c. henrys
   d. amperes
14. Asbestos insulation loses its insulating properties when it becomes
   a. overaged
   b. overheated
   c. used over a long period of time
   d. wet
15. How are solderless connectors installed on conductors?
   a. Bolted on
   b. Chemical compound
   c. Crimped on
   d. All of the above
16. The factor(s) governing the selection of wire size is/are
   a. (I^2R loss) in the line
   b. (IR drop) in the line
   c. current-carrying ability of the line
   d. all of the above
17. Enamel insulated conductors are usually called
   a. magnet wire
   b. high voltage wire
   c. low voltage wire
   d. transmission lines
18. The advantage of solderless connectors over soldered type connectors is that they are
   a. mechanically stronger
   b. easier to install
   c. free of corrosion
   d. all of the above
19. The basic requirement of any splice is that it be
   a. soldered
   b. mechanically and electrically as strong as the conductor that is spliced
   c. made with a splicer
   d. taped
20. The type of tape that is used for electrical circuits having a temperature of 175° F. or above is
   a. glass cloth
   b. plastic
   c. synthetic rubber compound
   d. impregnated cloth

CHAPTER 7

ELECTROMAGNETISM AND MAGNETIC CIRCUITS

The fundamental theories concerning simple magnets and magnetism were discussed in chapter 1 of this course. Those discussions dealt mainly with forms of magnetism that were not related directly to electricity—permanent magnets for instance. Only brief mention was made of those forms of magnetism having direct relation to electricity (such as ''producing electricity with magnetism''). This chapter resumes the study of magnetism where chapter 1 left off. Therefore, it may be necessary for you to review parts of chapter 1 from time to time. This chapter begins the more advanced study of MAGNETISM AS IT IS AFFECTED BY ELECTRIC CURRENT FLOW, and the closely related study of ELECTRICITY AS IT IS AFFECTED BY MAGNETISM. This general subject area is most often referred to as ELECTROMAGNETISM.

Magnetism and basic electricity are so closely related that one cannot be studied at length without involving the other. This close fundamental relationship will be continually borne out in other chapters of this course, such as in the study of generators, transformers, and motors. You will become familiar with many of the most general relationships between magnetism and electricity, such as the following:

1. Electric current flow will ALWAYS produce some form of magnetism.

2. Magnetism is by far the most commonly used means for producing or using electricity.

3. The peculiar behavior of electricity under certain conditions is caused by magnetic influences.

Magnetic Field Around a Current-Carrying Conductor

In 1819 Hans Christian Oersted, a Danish physicist, found that a definite relation exists between magnetism and electricity. He discovered that an electric current is accompanied by certain magnetic effects and that these effects obey definite laws. If a compass is placed in the vicinity of a current-carrying conductor, the needle alines itself at right angles to the conductor, thus indicating the presence of a magnetic force. The presence of this force can be demonstrated by passing an electric current through a vertical conductor which passes through a horizontal piece of cardboard, as illustrated in figure 7-1. The magnitude and direction of the force are determined by setting a compass at various points on the cardboard and noting the deflection.

The direction of the force is assumed to be the direction the north pole of the compass points. These deflections show that a magnetic field exists in circular form around the conductor. When the current flows upward, the field direction is clockwise, as viewed from the top, but if the polarity of the supply is reversed so that the current flows downward, the direction of the field is counterclockwise.

The relation between the direction of the magnetic lines of force around a conductor and the direction of current flow along the conductor may be determined by means of the LEFT-HAND RULE FOR A CONDUCTOR. If the conductor is grasped in the left hand with the thumb extended in the direction of electron flow (- to +), the fingers will point in the direction of the magnetic lines of force. This is the same direction in which the north pole of a compass would point if the compass was placed in the magnetic field.

Arrows generally are used in electric diagrams to denote the direction of current flow along the length of wire. Where cross sections of wire are shown, a special view of the arrow

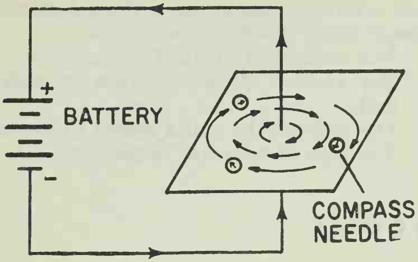


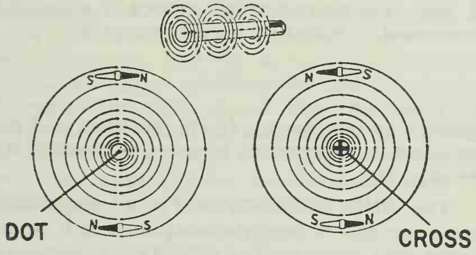
Figure 7-1.—Magnetic field around a current-carrying conductor.

is used. A cross-sectional view of a conductor that is carrying current toward the observer is illustrated in figure 7-2 (A). The direction of current is indicated by a dot, which represents the head of the arrow. A conductor that is carrying current away from the observer is illustrated in figure 7-2 (B). The direction of current is indicated by a cross, which represents the tail of the arrow.

When two parallel conductors carry current in the same direction, the magnetic fields tend to encircle both conductors, drawing them together with a force of attraction, as shown in figure 7-3 (A). Two parallel conductors carrying currents in opposite directions are shown in figure 7-3 (B). The field around one conductor is opposite in direction to the field around the other conductor. The resulting lines of force are crowded together in the space between the wires, and tend to push the wires apart. Therefore, two parallel adjacent conductors carrying currents in the same direction attract each other and two parallel conductors carrying currents in opposite directions repel each other.

Magnetic Field of a Coil

The magnetic field around a current-carrying wire exists at all points along its length. The field consists of concentric circles in a plane perpendicular to the wire. (See fig. 7-1.) When this straight wire is wound around a core, as shown in figure 7-4 (A), it becomes a coil and the magnetic field assumes a different shape. Part (A) is a partial cutaway view which shows the construction of a simple coil. Part (B) is a complete cross-sectional view of the same coil. The two ends of the coil are identified as *a* and *b*. When current is passed through the coiled conductor, as indicated, the magnetic field of each turn of wire links with the fields of adjacent turns, as explained in connection with figure 7-3 (A). The combined influence of all the turns produces a two-pole field similar to that of a simple bar magnet. One end of the coil will be a north pole and the other end will be a south pole.



CURRENT FLOWING OUT (A)

CURRENT FLOWING IN (B)

Figure 7-2.—Magnetic field around a current-carrying conductor, detailed view.

POLARITY OF AN ELECTROMAGNETIC COIL

In figure 7-2, it was shown that the direction of the magnetic field around a straight conductor depends on the direction of current flow through that conductor. Thus, a reversal of current flow through a conductor causes a reversal in the direction of the magnetic field that is produced. It follows that a reversal of the current flow through a coil also causes a reversal of its two-pole field. This is true because that field is the product of the linkage between the individual turns of wire on the coil. Therefore, if the field of each turn is reversed, it follows that the total field (coil's field) is also reversed.

When the direction of electron flow through a coil is known, its polarity may be determined by use of the LEFT-HAND RULE FOR COILS. This rule is illustrated in figure 7-5, and is stated as follows: GRASPING THE COIL IN THE LEFT HAND, WITH THE FINGERS "WRAPPED AROUND" IN THE DIRECTION OF ELECTRON

FLOW, THE THUMB WILL POINT TOWARD THE NORTH POLE.

STRENGTH OF AN ELECTROMAGNETIC FIELD

The strength, or intensity, of a coil's field depends on a number of factors. The major factors are listed below. All of these factors are discussed under headings that follow.

1. The number of turns of conductor.
2. The amount of current flow through the coil.
3. The ratio of the coil's length to its width.
4. The type of material in the core.

Magnetic Circuits

Many electrical devices depend upon magnetism in one or more forms for their operation. To have these devices function efficiently, engineers work out intricate designs for the required magnetic conditions. The magnets designed to do a particular job must have the required strength, and must be provided with paths, or circuits, of suitable shapes and materials.

A magnetic circuit is defined as the path (or paths) taken by the magnetic lines of force leaving a north pole, passing through the entire circuit and returning to the south pole. A magnetic circuit may be a series or parallel circuit or any combination.

Ohm's Law Equivalent for Magnetic Circuits

The law of current flow in the electric circuit is similar to the law for the establishing of flux in the magnetic circuit.

Ohm's law for ELECTRIC circuits states that the current is directly proportional to the applied voltage and inversely proportional to the resistance offered by the circuit. Expressed mathematically,

$$I = \frac{E}{R}.$$

Rowland's law for MAGNETIC circuits states, in effect, that the number of lines of magnetic flux in maxwells (Φ) is directly proportional to the magnetomotive force in gilberts (F) and inversely proportional to the reluctance ($\mathfrak{R}$) offered by the circuit. The unit of reluctance sometimes used is the REL, $\mathfrak{R}$. Expressed mathematically,

$$\Phi = \frac{F}{\mathfrak{R}}.$$

The similarity of Ohm's law and Rowland's law is apparent. However, the units used in the expression for Rowland's law need to be explained.

The MAGNETIC FLUX, Φ, (phi) is similar to current in the Ohm's law formula, and comprises the total number of lines of force existing in the magnetic circuit. The MAXWELL is the unit of flux—that is, 1 line of force is equal to 1 maxwell. However, the maxwell is often referred to as simply a LINE OF FORCE, LINE OF INDUCTION or LINE.

The MAGNETOMOTIVE FORCE, F, or m. m. f., comparable to electromotive force in the Ohm's law formula, is the force that produces the flux in the magnetic circuit. The practical unit of magnetomotive force is the AMPERE-TURN. Another unit of magnetomotive force sometimes used is the GILBERT, designated by the capital letter, F. The gilbert is the magnetomotive force required to establish 1 maxwell in a magnetic circuit having 1 unit of reluctance (1 rel). The magnetomotive force in gilberts is expressed in terms of ampere-turns as

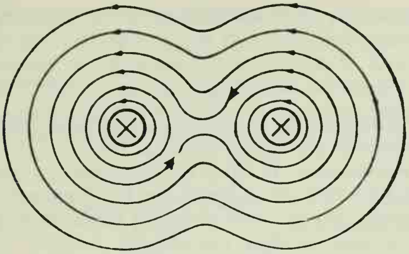
$$F = 1.257 IN,$$

where F is in gilberts, I is in amperes, and N is the number of complete turns of wire encircling the circuit.

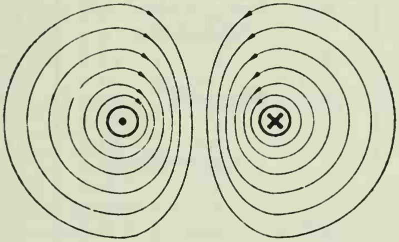
The UNIT OF INTENSITY of magnetizing force per unit of length is designated as H, and is sometimes expressed as gilberts per centimeter of length. Expressed mathematically,

$$H = \frac{1.257 IN}{l},$$

where l is the length in centimeters.



CURRENTS FLOWING IN THE SAME DIRECTION (A)



CURRENTS FLOWING IN OPPOSITE DIRECTIONS (B)

Figure 7-3.—Magnetic field around two parallel conductors.

The RELUCTANCE, $\mathfrak{R}$, similar to resistance in the Ohm's law formula, is the opposition offered by the magnetic circuit to the passage of magnetic flux. The unit of reluctance has not been named officially. However, the REL has been proposed, and the symbol $\mathfrak{R}$ is commonly used. The unit of reluctance is the reluctance of 1 centimeter-cube of air. The reluctance of a magnetic substance varies directly as the length of the flux path and inversely as the cross-sectional area and the permeability, μ, of the substance. Expressed mathematically,

$$\mathfrak{R} = \frac{l}{\mu A},$$

where l is the length in centimeters, and A is the cross-sectional area in square centimeters.

PERMEABILITY, designated by the Greek letter mu, μ, is treated under a separate heading. However, it is defined here to permit a fuller interpretation of Rowland's law and also a practical application of this law. Permeability is a measure of the relative ability of a substance to conduct magnetic lines of force as compared with air. The permeability of air is taken as 1. Permeability is indicated as the ratio of the flux density in lines per square centimeter (gauss,

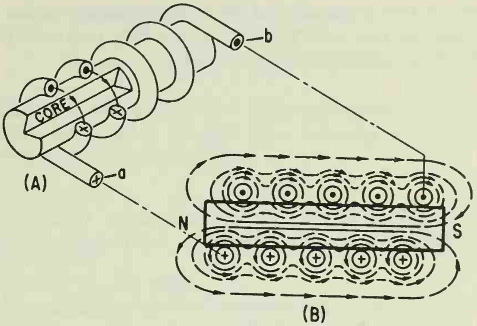


Figure 7-4.—Magnetic field produced by a current-carrying coil.

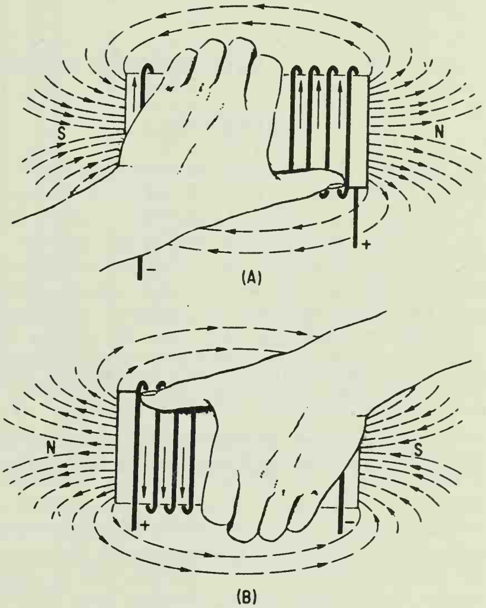


Figure 7-5.—Left-hand rule for coil polarity.

B) to the intensity of the magnetizing force in gilberts per centimeter of length, indicated by H. Expressed mathematically,

$$\mu = \frac{B}{H}.$$

Another term used in magnetic circuits is PERMEANCE. Permeance, indicated by the symbol, P, is the reciprocal of reluctance—that is,

$$P = \frac{1}{\mathfrak{R}}.$$

Values of B, H, and μ for common magnetic substances are given in table 7-1.

Permeance is like conductance in electric circuits, and is defined as the property of a magnetic circuit that permits lines of magnetic flux to pass through the circuit.

Table 7-1.—B, H, and μ for common magnetic material.*

B	Sheet steel		Cast steel		Wrought iron		Cast iron	
	H	μ	H	μ	H	μ	H	μ
3,000	1.3	2,310	2.8	1,070	2.0	1,500	5.0	600
4,000	1.6	2,500	3.4	1,177	2.5	1,600	8.5	471
5,000	1.9	2,630	3.9	1,281	3.0	1,666	14.5	347
6,000	2.3	2,605	4.5	1,332	3.5	1,716	24.0	250
7,000	2.6	2,700	5.1	1,371	4.0	1,750	38.5	182
8,000	3.0	2,666	5.8	1,380	4.5	1,778	60.0	133
9,000	3.5	2,570	6.5	1,382	5.0	1,800	89.0	101
10,000	3.9	2,560	7.5	1,332	5.6	1,782	124.0	80.6
11,000	4.4	2,500	9.0	1,222	6.5	1,692	166.0	66.4
12,000	5.0	2,400	11.5	1,042	7.9	1,520	222.0	54.1
13,000	6.0	2,166	16.0	813	10.0	1,300	290.0	44.8
14,000	9.0	1,558	21.5	651	15.0	934	369.0	38.0
15,000	15.5	970	32.0	469	25.0	600	....	...
16,000	27.0	594	49.0	327	49.0	327	....	...
17,000	52.5	324	74.0	230	93.0	183	....	...
18,000	92.0	196	115.0	156	152.0	118	....	...
19,000	149.0	127	175.0	108	229.0	83	....	...
20,000	232.0	86	285.0	70	....	....	....	...

*B = flux density in lines per square centimeter; H = gilberts per centimeter of length; μ = permeability; $\mu = \frac{B}{H}$.

A comparison of the units, symbols, and equations used in applying Ohm's law to electric circuits and Rowland's law to magnetic circuits is given in table 7-2.

Table 7-2.—Comparison of electric and magnetic circuits.

	Electric circuit	Magnetic circuit
Force.	Volt, E, or e.m.f.	Gilberts, F, or m.m.f.
Flow	Ampere, I	Flux, Φ, in maxwells
Opposition.	Ohms, R	Reluctance, $\mathfrak{R}$, or rels
Law.	Ohm's law, $I = \frac{E}{R}$	Rowland's law, $\Phi = \frac{F}{\mathfrak{R}}$
Intensity of force .	Volts per cm. of length	$H = \frac{1.257IN}{l}$, gilberts per centimeter of length.
Density.	Current density—for example, amperes per cm.^{2}.	Flux density—for example, lines per cm.^{2}, or gausses.

As a practical application of Rowland's law, let it be required to find the ampere-turns *(IN)* necessary to produce 20,000 lines of flux in a CAST STEEL ring having a cross-sectional area of 4 square centimeters and an average length of 20 centimeters, as shown in figure 7-6.

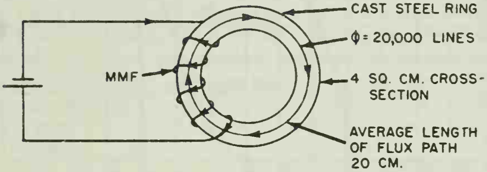


Figure 7-6.—Determining ampere-turns in a magnetic circuit.

Flux density B is expressed as

$$B = \frac{\Phi}{A} = \frac{200,000}{4} = 5,000 \text{ lines/cm.}^2,$$

and from table 7-1 the corresponding value of H for cast steel is 3.9. The formula for H has previously been given as

$$H = \frac{1.257 IN}{l},$$

from which

$$IN = \frac{Hl}{1.257}.$$

Substituting 3.9 for H and 20 for l in the preceding equation,

$$IN = \frac{3.9 \times 20}{1.257} = 62 \text{ ampere-turns.}$$

Properties of Magnetic Materials

PERMEABILITY

When an annealed sheet steel core is used in an electromagnet it produces a stronger magnet than if a cast iron core is used. This is true because annealed sheet steel is more readily acted upon by the magnetizing force of the coil than is hard cast iron. In other words, soft sheet steel is said to have greater permeability because the magnetic lines are established more easily in it than in cast iron. The ratio of the flux produced by a coil when the core is iron (or some other substance) to the flux produced when the core is air is called the PERMEABILITY of the iron (or whatever substance is used), the current in the coil being the same in each case. The permeability of a substance is thus a measure of the relative ability to conduct magnetic lines of force, or its magnetic conductivity. The permeability of air is 1. The permeability of nonmagnetic materials, such as wood, aluminum, copper, and brass is essentially unity, or the same as for air.

Magnetization curves for the four magnetic materials listed in table 7-1 are given in figure 7-7.

The permeability of magnetic materials varies with the degree of magnetization, being smaller for high values of flux density, as is indicated in table 7-1 and figure 7-8.

HYSTERESIS

The simplest method of illustrating the property of hysteresis is by graphical means such as the hysteresis loop shown in figure 7-9.

In this figure the magnetizing force is indicated in gilberts per centimeter of length along the plus and minus H axis, and the flux density is indicated in gausses along the plus and minus B axis. The intensity of the magnetizing force, H, applied by means of a current-carrying coil of wire around the sample of magnetic material, is varied uniformly through one cycle of operation, starting at zero. The force, H, is increased in the positive direction (current flowing in a given direction through the coil) to 11 gilberts per centimeter. During this time the flux density, B, increases from zero to 14,000 at point A. If H is decreased to zero, the descending curve of flux density does not return to zero via its rise path. Instead, it returns to point B, where the flux density is 13,000. The magnetic flux indicated by the length of line OB represents the RETENTIVITY of the magnetic substance.

Retentivity is the ability of a magnetic substance to retain its magnetism after the magnetizing force has been removed. Retentivity is most apparent in hard steel and is least apparent in soft iron.

The value of the RESIDUAL, or remaining, MAGNETISM when H has been reduced to zero, depends on the substance used and the degree

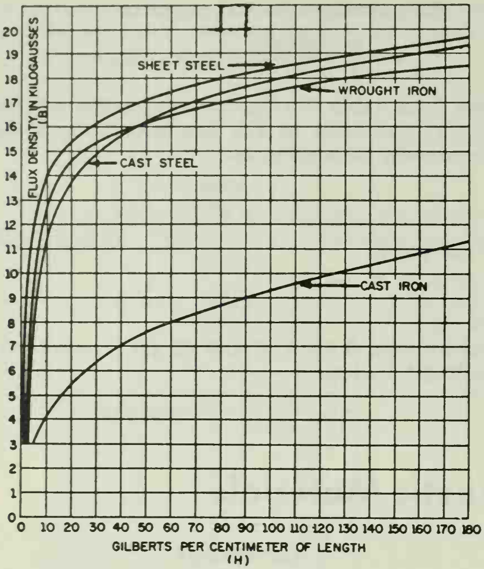


Figure 7-7.—Magnetization curves for four magnetic materials.

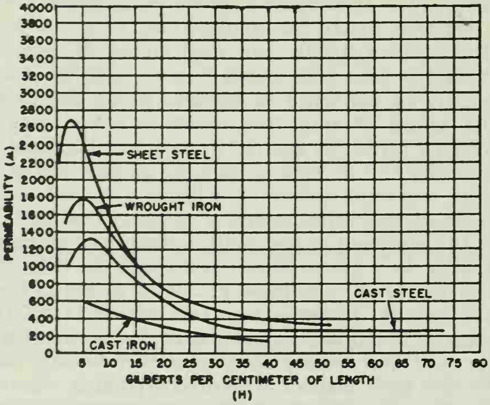


Figure 7-8.—Permeability curves.

of flux density attained. In this example the residual magnetism is 13,000 gausses.

If current is now sent through the coil in the opposite direction, so that the intensity of the magnetizing force becomes -*H*, the force will have to be increased to point *C* before the residual magnetism is reduced to zero. The magnetizing force, *OC*, necessary to reduce the residual magnetism to zero is called the COERCIVE FORCE. In this example the coercive force is **6 gilberts** per centimeter.

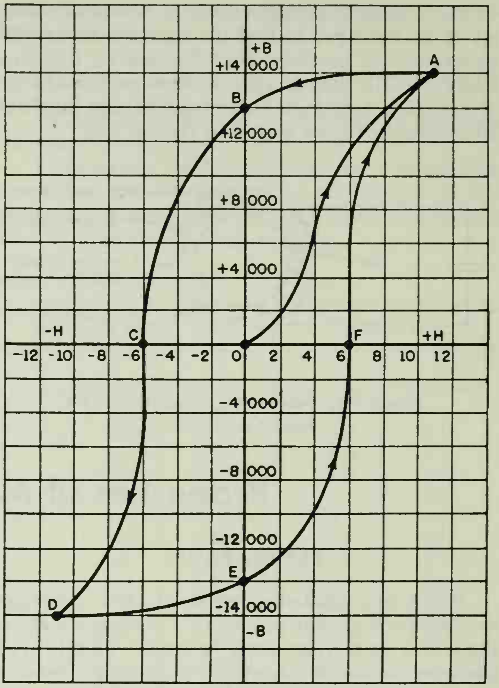


Figure 7-9.—Hysteresis loop.

If the magnetizing force is continued to **-11** gilberts per centimeter, the curve descends from *C* to *D*, magnetizing the sample of magnetic material with the opposite polarity. If the magnetizing force is reduced again to zero, the **flux** density is reduced to point *E*. The magnetic **flux** indicated by the length of line *OE* represents the retentivity of the magnetic substance, as **did** line *OB*. The residual magnetism is again **13,000** gausses.

If the current through the coil is again reversed (sent through in the original direction), the magnetization curve moves to zero when the magnetizing force is increased to point *F*.

Thus, when the magnetizing force goes through a complete cycle, the resulting magnetization likewise goes through a complete cycle.

From the foregoing analysis it is apparent that hysteresis is the property of a magnetic substance that causes the magnetization to lag behind the force that produces it. The lag of magnetization behind the force that produces it is caused by molecular friction. Energy is needed to move the molecules (or domains) through a cycle of magnetization. If the magnetization is reversed slowly, the energy loss may be negligible. However, if the magnetization is reversed rapidly, as when commercial alternating current is used, considerable energy may be dissipated. If the molecular friction is great, as when hard steel is used, the losses may be very great. Another factor that determines hysteresis loss is the maximum density of the flux established in the magnetic material.

A comparison of the hysteresis loops for annealed steel and hard steel is shown in figure 7-10. The area within each loop is a measure of the hysteresis energy loss per cycle of operation. Thus, as shown in the figure, more energy is dissipated in molecular friction in hard steel than in annealed steel. It is therefore important that substances having low hysteresis loss be used for transformer cores and similar a-c applications.

Electromagnets

An electromagnet is composed of a coil of wire wound around a core of soft iron. When direct current flows through the coil the core will become magnetized with the same polarity that the coil (solenoid) would have without the core. If the current is reversed, the polarity of both the coil and the soft-iron core is reversed.

The polarity of the electromagnet is determined by the left-hand rule in the same manner that the polarity of the solenoid in figure 7-5 was determined. If the coil is grasped in the left hand in such a way that the fingers curve around the coil in the direction of electron flow (- to +), the thumb will point in the direction of the north pole.

The addition of the soft-iron core does two things for the current-carrying coil, or solenoid. First, the magnetic flux is increased because the soft-iron core is more permeable than the air core; second, the flux is more highly concentrated. The permeability of soft iron is many times that of air, and therefore the flux density is increased considerably when a soft-iron core is inserted in the coil.

The magnetic field around the turns of wire making up the coil influences the molecules in the iron bar causing, in effect, the individual molecular magnets, or domains, to line up in the direction of the field established by the coil. Essentially the same effect is produced in a soft-iron bar when it is under the influence of a permanent magnet.

The magnetomotive force resulting from the current flow around the coil does not increase the magnetism that is inherent in the iron core, it merely reorientates the ‘‘atomic’’ magnets that were present before the magnetizing force was applied. If substantial numbers of the tiny magnets are orientated in the same direction, the core is said to be magnetized.

When soft iron is used, most of the atomic magnets return to what amounts to a miscellaneous orientation upon removal of the magnetizing current, and the iron is said to be demagnetized. If hard steel is used, more of them will remain in alinement with the direction of the flux produced by the flow of current through the coil, and the metal is said to be a permanent magnet. Soft iron and other magnetic materials having high permeability and low retentivity are generally used in electromagnets.

It is known from experience that a piece of soft iron is attracted to either pole of a permanent magnet. A soft-iron bar is likewise attracted by a current-carrying coil, if the coil and bar are orientated as in figure 7-11. As shown in the figure, the lines of force extend through the soft iron and magnetize it. Because unlike poles attract, the iron bar is pulled toward the coil. If the bar is free to move, it will be drawn into the coil to a position near the center where the field is the strongest.

The SOLENOID-AND-PLUNGER TYPE of magnet in various forms is employed extensively aboard ships and aircraft. These are used to operate the feeding mechanism of carbon-arc searchlights; to open circuit-breakers automatically when the load current becomes excessive; to close switches for motorboat starting; to fire guns; and to operate flood valves, magnetic brakes, and many other devices.

The ARMATURE-TYPE of electromagnet also has extensive applications. In this type of magnet the coil is wound on and insulated from the iron core. The core is not movable. When

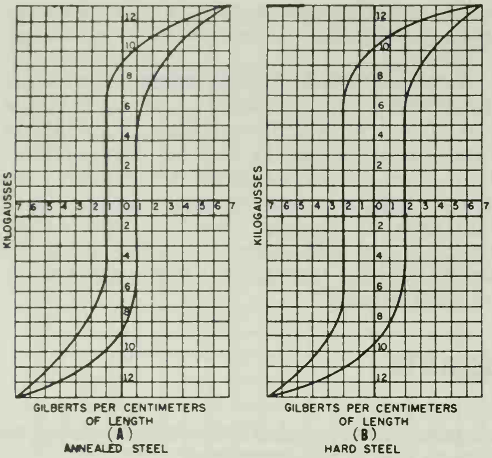


Figure 7-10.—Comparison of hysteresis loops.

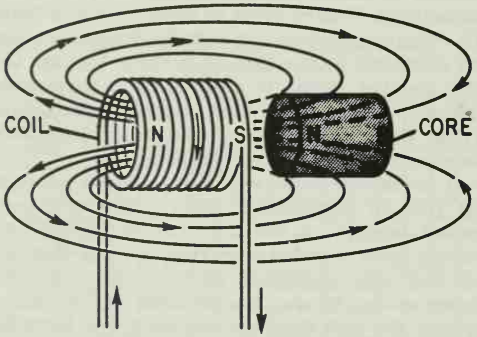


Figure 7-11.—Solenoid with iron core.

current flows through the coil the iron core becomes magnetized and causes a pivoted soft-iron armature located near the electromagnet, to be attracted toward it. This type of magnet is used in door bells, relays, circuit breakers, telephone receivers, and so forth.

APPLICATIONS OF ELECTROMAGNETS

Electric Bell

The electric bell is one of the most common devices employing the electromagnet. A simple electric bell is shown in figure 7-12. Its operation is explained as follows:

1. When the switch is closed, current flows from the negative terminal of the battery, through the contact points, the spring, the two coils, and back to the positive terminal of the battery.
2. The cores are magnetized, and the soft-iron armature (magnetized by induction) is pulled down, thus causing the hammer to strike the bell.
3. At the instant the armature is pulled down, the contact is broken, and the electromagnet loses its magnetism. The spring pulls the armature up so that contact is reestablished, and the operation is repeated. The speed with which the hammer is moved up and down depends on the stiffness of the spring and the mass of the moving element.

The magnetomotive forces of the two coils are in series aiding and therefore the magnetization of the core is increased over that produced by one coil alone.

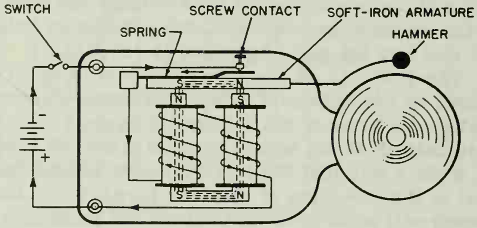


Figure 7-12.—Electric bell.

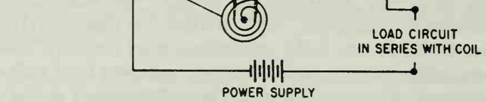


Figure 7-13.—Magnetic circuit breaker.

Circuit Breaker

A circuit breaker, like a fuse, protects a circuit against short circuits and overloading. In this device the winding of an electromagnet is connected in series with the load circuit to be protected and with the switch contact points. The principle of operation is shown in figure 7-13. Excessive current through the magnet winding causes the switch to be tripped, and the circuit to both breaker and load is opened by a spring. When the circuit fault has been cleared, the circuit is closed again by manually resetting the circuit breaker.

Many more applications of electromagnets are discussed throughout this course. Their applications to generators, motors, voltage regulators, reverse current relays, and servomechanisms will be covered.

QUIZ

1. Reversing the current flow through a coil
   a. reduces the amount of flux produced
   b. reverses its two-pole field
   c. reduces power consumed
   d. reduces eddy currents

2. The unit of magnetic flux is
   a. ampere-turn
   b. gilbert
   c. intensity
   d. maxwell

3. Flux in a magnetic circuit compares in an electrical circuit with
   a. voltage
   b. current
   c. resistance
   d. opposition

4. If a compass is placed in the vicinity of a conductor carrying d.c., the needle alines itself
   a. in the direction of current flow in the conductor
   b. at the right angles to the conductor
   c. in the general direction of the north pole
   d. in the general direction of the south pole

5. The left-hand rule for coils states: Grasping the
   a. coil with the left hand, with fingers pointing in the direction of the magnetic field, the middle finger will point to the north pole
   b. coil with the left hand, thumb pointing in the direction of the conductor movement, the fingers will point in the direction of the magnetic field
   c. conductor with the left hand, fingers pointing in the direction of the north pole, the thumb will indicate current flow
   d. coil in the left hand, fingers wrapped around in the direction of electron flow, the thumb will point towards north pole

6. The word permeability indicates the
   a. amount of reluctance of one centimeter-cube of air
   b. number of turns of an air core
   c. ability of a substance to conduct magnetic lines of force
   d. m.m.f. required to produce one gilbert

7. If an iron core is inserted part way into a coil and current is applied to the coil, the core will be drawn into the coil in an effort to
   a. increase reluctance of the magnetic circuit
   b. decrease the length of the magnetic circuit
   c. reduce the permeability of the circuit
   d. increase the residual effect

8. Current flow in a straight conductor produces
   a. hysteresis
   b. magnetic lines of force
   c. a north pole
   d. permeability

9. The inductance of a coil depends upon the
   a. number of turns, current flow, type of core material, and ratio of coil's length to its width
   b. current, flux, and core material
   c. direction of rotation, flux, and speed
   d. permeability, reluctance, gausses, and maxwells

10. The ability of a magnetic substance to hold its magnetism after the magnetizing force has been removed is
    a. residual
    b. retentivity
    c. hysteresis
    d. permeability

11. The solenoid and plunger type of magnet is employed in various forms to control
    a. electrical equipment
    b. hysteresis losses
    c. permeability
    d. all of the above

12. When using the left-hand rule for a conductor
    a. grasp the conductor with fingers pointing in the direction of current flow and thumb will indicate direction of field
    b. the compass will point in the direction of current flow and fingers will indicate direction of magnetic field
    c. grasp the conductor with the thumb extended in the direction of electron flow, the fingers will point in the direction of the magnetic lines of force
    d. reverse the current flow and thumb will point in direction of the magnetic field

13. The magnetic circuit is determined by
    a. lines of force leaving the south pole and entering the north pole externally
    b. permeability to current and the north pole
    c. maxwells to length in centimeters and the south pole
    d. the complete path taken by magnetic lines leaving the north pole, and returning to the north pole
14. In what material is retentivity most apparent?
    a. Hard steel
    b. Soft iron
    c. Copper
    d. Wood
15. The armature type of electromagnet
    a. has a movable iron bar in its magnetic circuit
    b. uses a permanent magnet core
    c. has a hard steel core and a pivoted bar of copper
    d. has a movable iron core
16. When two parallel conductors carrying current in the same direction are placed side by side, the fields produced by both
    a. cancel each other's field
    b. push each other apart
    c. form a north pole
    d. encircle each other, drawing the conductors together
17. The equivalent Ohm's law formula for magnetic circuits is
    a. $I = \frac{e}{r}$
    b. $R = \frac{I}{E}$
    c. $\Phi = \frac{E}{R}$
    d. $P = \frac{I}{E}$
18. Which of the following materials incurs low hysteresis loss when used for transformer cores and similar applications?
    a. Hard steel
    b. Annealed steel
    c. Soft iron
    d. Cast steel

19. The magnetic field around a current-carrying wire
    a. is parallel to the current flow in the conductor
    b. exists at all points along its length
    c. exists only at the beginning of electron movement
    d. moves in the direction of current flow

20. Direct current flows through a coil of wire which has an iron core. When the iron core is removed and all other factors remain unchanged, the total number of lines of force through the coil will change because
    a. changing the core material affects m.m.f.
    b. permeance has been increased
    c. reluctance has been increased
    d. the permeability of the magnetic circuit has been increased

21. When loops of wire are formed into a coil and current is passed through this coil
    a. the result is a permanent magnet
    b. each turn will cancel the magnetic field of each adjacent turn
    c. the magnetic field of each turn of wire links with the fields of adjacent turns
    d. permeability decreases to minimum

CHAPTER 8

INTRODUCTION TO ALTERNATING-CURRENT ELECTRICITY

In the study of batteries you learned that electrons flow continually in one direction—from the negative terminal to the positive terminal, via the load.

In the case of alternating current, electrons are made to move first in one direction and then in the other. The direction of current flow reverses periodically.

Basic A-C Generator

An alternating-current generator converts mechanical energy into electrical energy. It does this by utilizing the principle of electromagnetic induction. In the study of magnetism, it was shown that a current-carrying conductor produces a magnetic field around itself. It is also true that a changing magnetic field may produce an e.m.f. in a conductor. If a conductor lies in a magnetic field, and either the field or conductor moves, an e.m.f. is induced in the conductor. This effect is called electromagnetic induction.

CYCLE

Figure 8-1 shows a suspended loop of wire (conductor) being rotated (moved) in a counterclockwise direction through the magnetic field between the poles of a permanent magnet. For ease of explanation, the loop has been divided into a dark and a light half. Notice that in part (A), the dark half is moving along (parallel to) the lines of force. Consequently, it is cutting none of these lines. The same is true of the light half, moving in the opposite direction. Since the conductors are cutting no lines of force, no e.m.f. is induced. As the loop rotates toward the position shown in part (B), it cuts more and more lines of force per second because it is cutting more directly across the field (lines of force) as it approaches the position shown in (B). At position (B) the induced voltage is greatest because the conductor is cutting directly across the field.

As the loop continues to be rotated toward the position shown in part (C), it cuts fewer and fewer lines of force per second. The induced voltage decreases from its peak value. Eventually, the loop is once again moving in a plane parallel to the magnetic field, and no voltage (zero voltage) is induced. The loop has now been rotated through half a circle (one alternation, or 180°). The sine curve shown in the lower part of the figure shows the induced voltage at every instant of rotation of the loop. Notice that this curve contains 360°, or two alternations. Two alternations represent one complete cycle of rotation.

The direction of current flow during the rotation from (B) to (C), when a closed path is provided across the ends of the conductor loop, can be determined by using the LEFT-HAND RULE FOR GENERATORS. The left-hand rule is applied as follows: Extend the left hand so that the THUMB points in the direction of conductor movement, and the FOREFINGER points in the direction of magnetic flux (north to south). By pointing the MIDDLE FINGER 90 degrees from the forefinger, it will point in the direction of current flow within the conductor.

Applying the left-hand rule to the dark half of the loop in part (B), you will find that the direction of current flow is as shown by the heavy arrow. Similarly, you can determine the direction of current flow through the light half of the loop. The two induced voltages add together to form one total e.m.f. When the loop is further rotated to the position shown in part (D), the action is reversed. The dark half is moving

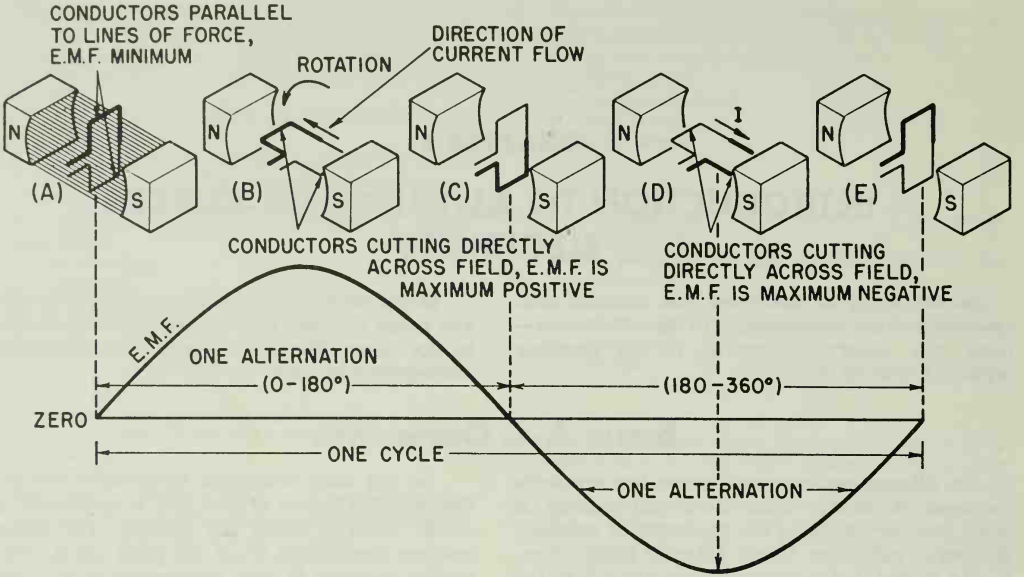

CONDUCTORS PARALLEL TO LINES OF FORCE, E.M.F. MINIMUM
ROTATION
DIRECTION OF CURRENT FLOW
N
S
I
(A)
(B)
(C)
(D)
(E)
CONDUCTORS CUTTING DIRECTLY ACROSS FIELD, E.M.F. IS MAXIMUM POSITIVE
CONDUCTORS CUTTING DIRECTLY ACROSS FIELD, E.M.F. IS MAXIMUM NEGATIVE
E.M.F.
ONE ALTERNATION
(0-180°)
(180-360°)
ZERO
ONE CYCLE
ONE ALTERNATION

Figure 8-1.—Basic alternating-current generator.

up instead of down, and the light half is moving down instead of up. By applying the left-hand rule once again, you will find that the direction of the induced e.m.f. and its resulting current have reversed. The voltage builds up to maximum in this new direction, as shown by the sine-wave tracing. The loop finally returns to its original position (part E), at which point voltage is again zero. The wave of induced voltage has gone through one complete cycle.

If the loop is rotated at a steady rate, and if the strength of the magnetic field is uniform, the number of cycles per second and the voltage will remain at fixed values. Continuous rotation will produce a series of sine-wave voltage cycles, or, in other words, an a-c voltage. In this way mechanical energy is converted into electrical energy.

The rotating loop in figure 8-1 is called an armature. The armature may have any number of loops or coils.

FREQUENCY

The frequency of an alternating current or voltage is the number of complete cycles occurring in each second of time. Hence, the speed of rotation of the loop determines the frequency. For a single loop rotating in a two-pole field you can see that each time the loop makes one complete revolution the current reverses direction twice. A single cycle of a-c per second will result if the loop makes one revolution each second. If it makes two revolutions per second, the output frequency will be two cycles per second. In other words, the frequency of a two-pole generator happens to be the same as the number of revolutions per second. As the speed is increased, the frequency is increased.

If an alternating-current generator has four pole pieces, as in figure 8-2, every complete mechanical revolution of the armature will produce TWO a-c cycles. When the dark half of the loop passes between poles *S*1 and *N*2, a voltage is induced which causes current to flow into the dark slipring attached to the end of the loop.

When the dark half passes between *N*2 and *S*2, the induced voltage reverses direction. Another reversal occurs when it passes between *S*2 and *N*1. The voltage at the sliprings reverses direction FOUR TIMES during each revolution. In other words, two cycles of a-c voltage are generated for each mechanical revolution. If each revolution lasts one second, the frequency of the output is two cycles per second. The more poles that are added, the higher the frequency per revolution becomes. To find the output frequency of any a-c generator, the following formula can be used:

$$f = \frac{P \times \text{r.p.m.}}{120}$$

where f is frequency in cycles per second, r.p.m. is revolutions per minute, and P is the number of poles.

A generator made to deliver 60 cycles per second (c.p.s.), having two field poles, would need an armature designed to rotate at 3,600 r.p.m. If it had four field poles, it would need an armature designed to rotate at 1,800 r.p.m. In either case, frequency would be the same. In actual practice, a generator designed for low-speed operation generally has a greater number of pole pieces, while a high-speed machine will have relatively fewer pole pieces, if both are to deliver power at the same frequency.

PERIOD

The period of an a-c voltage or current of sine waveform is the time for one complete cycle, or $1/f$. For example, the period of a 60-cycle voltage is 1/60 of a second; that of a 50-cycle voltage is 1/50 second.

GENERATED VOLTAGE

Alternating-current generators are usually constant-potential machines because they are driven at constant speed and have fixed magnetic field strength for a given load. The effective voltage, E, generated by a single-winding (phase) a-c generator is related to the total field strength per pole, Φ; the frequency, f; and the total number of active conductors, N, in the armature winding; as indicated in the following equation:

$$E = 2.22\,\Phi f N 10^{-8}$$

For example, if $\Phi = 2.5 \times 10^6$, $f = 60$ cycles per second, and $N = 96$ conductors, the voltage generated is

$$E = 2.22 \times 2.5 \times 10^6 \times 60 \times 96 \times 10^{-8}$$

$$E = 320 \text{ volts.}$$

(The factors of poles (P) and speed (S in r.p.m.), which appear in the equation for generated voltage in multipolar series-wound d-c generators, do not appear in the formula for the voltage generated in each phase of the a-c generator. This is because they are replaced by the equivalent factor of frequency ($f = \frac{PS}{120}$).

The length of active conductor extending under a pole does not appear in the equation directly because it is included in the factor of total magnetic flux per pole. The longer the active conductor, the more flux there will be for each pole, since the pole length and conductor length are assumed to be the same. For example, if an active conductor length is doubled, the pole length is doubled, the flux per pole is doubled, and the generated voltage is doubled.

Analysis of Sine Wave of Voltage

VECTORS DEFINED

As mentioned previously, an alternating current or voltage is one in which the direction changes periodically. The electron movement is first in one direction, then in the other. The variation is of sine waveform. Straight lines drawn to scale, called VECTORS, are used in solving problems involving sine-wave currents and voltages.

A simple vector is a straight line used to denote the magnitude and direction of a given quantity. Magnitude is denoted by the length of the line, drawn to scale, and direction is indicated by an arrow at one end of the line, together with the angle that the vector makes with a horizontal reference vector.

For example, if a certain point B (fig. 8-3) lies 1 mile east of point A, the direction and distance from A to B can be shown as vector e by using a scale of approximately 1/2 inch = 1 mile.

Vectors may be rotated like the spokes of a wheel to generate angles. Positive rotation is counterclockwise and generates positive angles. Negative rotation is clockwise and generates negative angles.

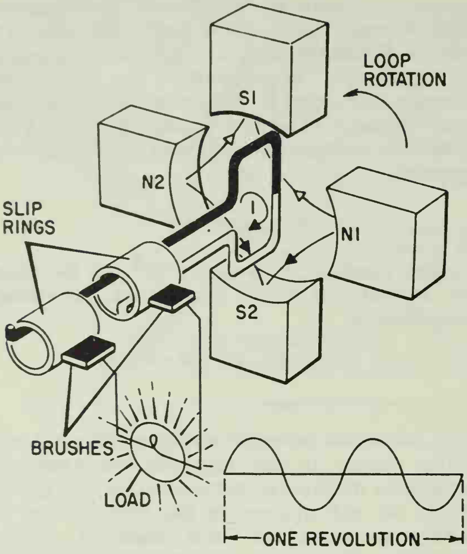


Figure 8-2.—Four-pole basic a-c generator.

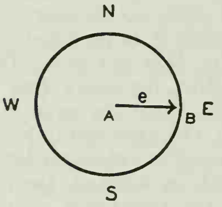


Figure 8-3.—Designating direction and distance by vectors.

The vertical projection (dotted line in fig. 8-4) of a ROTATING VECTOR may be used to represent the voltage at any instant. Vector E_m represents the maximum voltage induced in a conductor rotating at uniform speed in a 2-pole field (points 3 and 9). The vector is rotated counterclockwise through one complete revolution (360°). The point of the vector describes a circle. A line drawn from the point of the vector perpendicular to the horizontal diameter of the circle is the vertical projection of the vector.

The circle also describes the path of the conductor rotating in the bi-polar field. The vertical projection of the vector represents the voltage generated in the conductor at any instant corresponding to the position of the rotating vector as indicated by angle θ . Angle θ represents selected instants at which the generated voltage is plotted. The sine curve plotted at the right of the figure represents successive values of the a-c voltage induced in the conductor as it moves at uniform speed through the 2-pole field because the instantaneous values of rotationally induced voltage are proportional to the sine of the angle θ that the rotating vector makes with the horizontal.

EQUATION OF SINE WAVE OF VOLTAGE

The sine curve is a graph of the equation

$$e = E_m \sin \theta,$$

where e is the instantaneous voltage, E_m is the maximum voltage, θ is the angle of the generator armature, and "sine" is one of the trigonometric functions shown in figure 8-4.

The instantaneous voltage, e, depends on the sine of the angle. It rises to a maximum positive value as the angle reaches 90°. This occurs because the conductor cuts directly across the flux at 90°. It falls to zero at 180°, because the conductor cuts no lines of flux at 180°. It reaches a negative peak at 270°, and becomes zero again at 360°. For example, when $\theta = 60°$ and $E_m = 100$ volts, $e = 100 \times \sin 60° = 86.6$ volts. When $\theta = 240°$, $e = 100 \sin 240° = -86.6$ volts.

Another form of the trigonometric equation for a sine wave of voltage involves the angular velocity of its rotating vector. The term "angular velocity" refers to the number of degrees (angles) through which a voltage vector rotates per second. Angular velocity is symbolized by the Greek letter omega (ω). In practice, ω is generally given in terms of RADIANS per second, rather than degrees per second. A radian is a segment of the circumference of a circle. This segment is always exactly equal in length to the RADIUS of that circle. There are π (3.14) radians in half a circle, and 2π (6.28) radians in the circumference of a complete circle. Therefore, when a voltage vector makes one complete revolution, describing one complete circle, it traverses 2π or 6.28 radians. In terms of degrees of rotation, one radian is 360°/6.28 or 57.32°.

The number of radians per second traversed by an alternating-voltage vector is

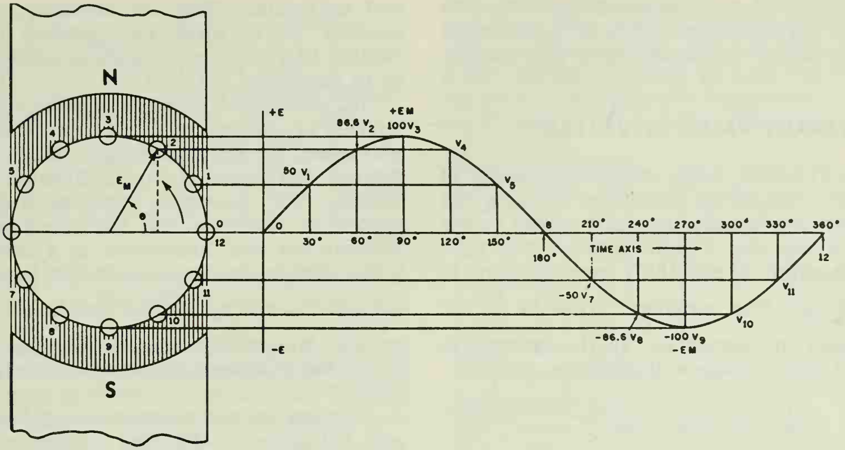


Figure 8-4.--Generation of sine-wave voltage.

closely related to its frequency, because either may be used to express the other. Since one vector revolution equals one complete cycle, then each cycle equals 6.28 radians of vector travel. That is, an alternating voltage whose frequency is 60 cycles would be said to have an angular velocity of 6.28 x 60, or roughly 377 radians per second. Written as a formula, angular velocity is $\omega = 2\pi f$. Thus, in a formula involving angular velocity, the term $2\pi f$ may be replaced by the simpler symbol ω, if convenient. As previously stated, another form of the trigonometric equation for a sine wave of voltage involves the angular velocity of the generating vector.

The equation is

$$e = E_m \times \sin \omega t.$$

It is used to determine the voltage of a rotating vector at some given instant of time. The starting reference, or "time zero," is usually when the voltage vector is at a peak positive value. The equation time factor t is the elapsed time from time zero, and is the exact instant at which the voltage is to be determined. To determine the exact angular position at any instant, multiply the angular velocity (ω) of the vector by the time elapsed (t). By dividing elapsed time t by the period for one cycle, and multiplying by 360°, the angular position of the voltage vector may be determined for any instant. Multiplying E_m by the sine of that instantaneous angle will yield the instantaneous voltage e.

For example, consider a 60-cycle voltage whose peak value is 100 volts. Assume you must determine the voltage 0.00139 second after the voltage has reached a positive peak.

$$\sin t = \sin 2\pi f t = \sin 360(60)(0.00139) = \sin 30° = 0.5$$

The instantaneous voltage e is

$$e = E_m \times \sin 30°$$

$$e = 100 \times 0.5$$

$$e = 50 \text{ volts.}$$

There are four important values associated with sine waves of voltage or current:

Instantaneous—designated as e or i; maximum—designated as E_m or I_m; average—designated as E_{avg} or I_{avg}; and effective—designated as E or I.

The INSTANTANEOUS value may be any value between zero and maximum depending on the instant chosen, as indicated by the equation $e = E_m \sin \omega t$.

The MAXIMUM value of voltage is reached twice each cycle and is the greatest value of instantaneous voltage generated during each cycle.

The ratio of the instantaneous value of voltage to the maximum value is equal to the sine of the angle corresponding to that instant.

AVERAGE VALUE OF VOLTAGE

The AVERAGE value of a sine wave of voltage or current is found by dividing the area under one alternation (half cycle) by the distance along the X axis between two successive instants (0° and 180°) corresponding to zero voltage. The average value is $\frac{2}{\pi}$, or 0.637, times the maximum. In the example in figure 8-5, the average voltage is

$$\frac{2}{\pi} \times 100, \text{ or } 63.7 \text{ volts.}$$

Thus,

$$E_{avg} = 0.637\ E_{max}$$

EFFECTIVE OR R.M.S. VALUE

The EFFECTIVE value of an a-c voltage or current of sine waveform is defined in terms of the equivalent heating effect of a direct current.

Heating effect is INDEPENDENT of direction of electron flow and varies as the square of the instantaneous current. Thus, an alternating current of sine waveform having a maximum value of 14.14 amperes produces the same amount of heat in a circuit having a resistance of 1 ohm that a direct current of 10 amperes produces. The effective value of this alternating current is equal to 0.707 of the maximum value. Thus, $I_{eff} = 0.707\ I_{max}$, or $0.707 \times 14.14 = 10$ amperes. The effective value is also known as the ROOT-MEAN-SQUARE (r.m.s.) value because it is the square root of the average of the squared values between zero and maximum. Thus an effective, or r.m.s. current of 10 amperes produces the same heating in a given resistance as a direct current of 10 amperes.

In practice, r.m.s. values of voltage and current are more important than instantaneous, maximum, or average values. Most a-c voltmeters and ammeters are calibrated in r.m.s. values. For example, suppose that an a-c voltmeter indicates that the effective voltage between the two conductors in a cable is 440 volts. Twice in each cycle the insulation is subject to a voltage stress that is $\frac{E_m}{E} = \frac{1}{0.707}$, or 1.41 times 440 volts, or 620 volts; where E_m is the maximum voltage and E is the r.m.s. value.

Suppose an a-c ammeter in the same circuit indicates an effective current of 10 amperes. Twice in each cycle the current exceeds this value by 41 percent but the average heating effect is that which a direct current of 10 amperes would produce. Thus, the conductor size is based on the ammeter indication (r.m.s. current) rather than on the maximum value, even though the insulation stress is always 41 percent higher than the voltmeter indication.

The ratio of the effective value to the average value of a wave is called the FORM FACTOR and for all sine waves is equal to $\frac{0.707}{0.637}$ or 1.11. The form factor for waveforms such as flattop waves is less than 1.11. For waveforms such as peaked waves the form factor is greater than 1.11. If a waveform is not that of a sine wave the constants for effective and average values do not apply. Most electrical power and lighting circuits have sine-wave currents and voltages and the effective values indicated by voltmeters and ammeters are appropriate.

Combining A-C Voltages

Vectors may be used to combine a-c voltages of sine waveform and of the same frequency. The angle between the vectors indicates the time difference between their positive maximum values. The length of the vectors represents either the effective value or the positive maximum value, as desired.

The sine wave voltages generated in coils *a* and *b* of the simple generators (fig. 8-6(A)) are 90° out of phase because the coils are located 90° apart on the two-pole armatures. The armatures are on a common shaft. When coil *a* is cutting squarely across the field, coil *b* is moving parallel to the field and not

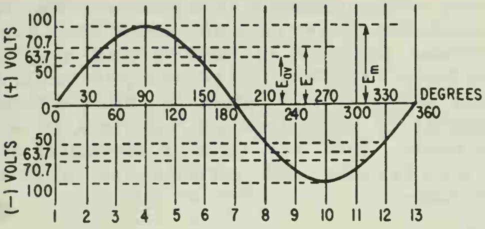


Figure 8-5.–Relative values of an a-c sine-wave voltage.

cutting through it. Thus, the voltage in coil *a* is maximum when the voltage in coil *b* is zero. If the frequency is 60 cycles per second, the time difference between the positive maximum values of these voltages is $\frac{90}{360} \times \frac{1}{60} = 0.00416$ second.

Vector E_a leads vector E_b by 90° in figure 8-6 (B) and sine wave *a* leads sine wave *b* by 90° in figure 8-6 (C). The curves are shown on separate axes to identify them with their respective generators; they are also projected on a common axis to show the relation between their instantaneous values. If coils *a* and *b* are connected in series and the maximum voltage generated in each coil is 10 volts, the total voltage is not 20 volts because the two maximum values of voltage do not occur at the same instant, but are separated one-fourth of a cycle. The voltages cannot be added arithmetically because they are out of phase. These values, however, can be added vectorially.

E_c in figure 8-6 (B) is the vector sum of E_a and E_b, and is the diagonal of the parallelogram, the sides of which are E_a and E_b. The effective voltage in each coil is 0.707 x 10 or 7.07 volts (where 10 volts is the maximum) and represents the length of the sides of the parallelogram. The effective voltage of the series combination is $7.07 \times \sqrt{2}$ or 10 volts and represents the length of the diagonal of the parallelogram.

Curve *c* in figure 8-6 (C) represents the sine wave variations of the total voltage E_c developed in the series circuit connecting coils *a* and *b*. Voltage E_a leads E_b by 90°. Voltage E_c lags E_a by 45°, and leads E_b by 45°.

Counterclockwise rotation of the vectors is considered positive rotation thus giving the sense of lead or lag. Thus, if E_a and E_b (fig. 8-6 (B)) are rotated counterclockwise, and their movement observed from a fixed position, E_a will pass this position first, then 90° later E_b will pass the position. Thus E_b lags E_a by 90°. If the maximum voltage in each coil is 10 volts, the maximum value of the combined voltage will be $10 \times \sqrt{2}$ or 14.4 volts. (See fig. 8-6 (C)).

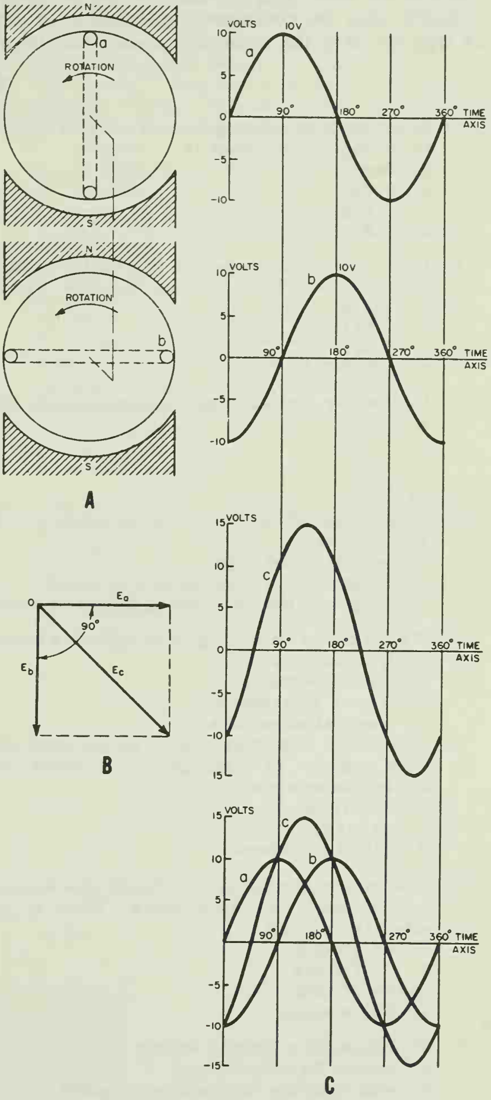


Figure 8-6.–Combining a-c voltages.

The important point to be made in this discussion is that two out-of-phase voltages may be resolved into a single resultant value by the use of vectors. Though generated voltages were used to illustrate the point in this case, the same rules apply to VOLTAGE DROPS as well. Any number of out-of-phase voltages may be combined vectorially, as long as they all have the same frequency; that is, as long as they remain a fixed number of degrees apart, like the two generator loops. Their magnitudes (LENGTH of their vectors) may be different. You will find vectors quite useful in the section of this course that deals with the effects of capacitors and inductors on a-c circuits. They are used to determine a-c impedances and currents, as well as voltages.

QUIZ

1. In formula form, angular velocity as applied to voltage or current is
   a. $2\ \omega$
   b. $2\ \pi\omega$
   c. $2\ \pi\ F$
   d. $2\ F$

2. How much larger is the maximum voltage value than the effective voltage value?
   a. 1.414
   b. 1.111
   c. 0.707
   d. 0.637

3. How many radians are in a complete circle?
   a. 0.707
   b. 1.11
   c. 3.14
   d. 6.28

4. Magnitude of a vector is denoted by the
   a. time axis
   b. length of the line
   c. length of the line, drawn to scale
   d. length of the time axis, drawn to scale

5. Which of the following best defines a cycle?
   a. One alternation
   b. Two alternations
   c. Three alternations
   d. Four alternations

6. The most important value associated with sine waves of voltage or current are
   a. instantaneous
   b. maximum
   c. average
   d. all of the above

7. The maximum value of a single sine wave of a-c voltage is 141.4 volts. What is the effective value?
   a. 63.7 volts
   b. 70.7 volts
   c. 99.97 volts
   d. 141.4 volts

8. Direction of a simple vector
   a. cannot be determined
   b. will indicate the reference point
   c. is indicated by an arrow at one end of the line
   d. is indicated by the magnitude

9. Frequency as applied to alternating current or voltage is the number of
   a. r.p.m. per second of time
   b. cycles per second of time
   c. poles per second of time
   d. volts generated per second of time

10. The effective value of an a-c voltage or current of sine waveform is defined in terms of the equivalent d.c.
    a. ''voltage effect''
    b. ''current effect''
    c. ''heating effect''
    d. ''cooling effect''

11. The average value of a single sine wave of a-c current is 63.7 amps. What is the r.m.s. value?
    a. 63.7 amps
    b. 70.7 amps
    c. 141.4 amps
    d. 156.95 amps

12. The instantaneous value of induced voltage of a single-phase generator
    a. will never be zero
    b. depends on the sine of the angle
    c. will always be the same
    d. depends on the cosine of the angle

13. The period of a-c voltage of sine waveform is the time required for one complete
    a. r.p.m.
    b. alternation
    c. cycle
    d. degree

14. The ''root-mean-square'' value is also known as the
    a. average value
    b. peak value
    c. instantaneous value
    d. effective value

15. Two voltages of the same frequency ''120 cycles per second'' have their positive maximum values displaced by 90°. What is the time difference between the phases?
    a. 0.00208 sec.
    b. 0.00416 sec.
    c. 0.02080 sec.
    d. 0.04160 sec.

16. Positive rotation of a vector is
    a. clockwise
    b. counterclockwise
    c. either clockwise or counterclockwise
    d. neither clockwise nor counterclockwise
17. The effective generated voltage of a single-phase a-c generator may be obtained by the formula
    a. $E = 1.111 \ \Phi fD10^{-8}$
    b. $E = 2.22 \ \Phi fN^{-6}$
    c. $E = 1.111 \ \Phi FD^{-6}$
    d. $E = 2.22 \ \Phi fN10^{-8}$
18. Most a-c voltmeters and ammeters are calibrated in
    a. r.m.s. values
    b. average values
    c. peaks values
    d. instantaneous values
19. A radian is always equal to
    a. the circumference of the circle
    b. the radius of the circle
    c. pi
    d. 60 degrees
20. Angular velocity is symbolized by the Greek letter
    a. gamma γ
    b. mu μ
    c. omega ω
    d. beta β
21. If an active conductor's length is doubled, the
    a. pole length is cut in half
    b. flux per pole is cut in half
    c. generated voltage is doubled
    d. generated voltage is tripled
22. The "form factor" in most cases refers to the ratio of
    a. average value to maximum value
    b. instantaneous value to maximum value
    c. r.m.s. value to effective value
    d. r.m.s. value to average value
23. Conductor size in an a-c circuit is based on
    a. instantaneous current
    b. maximum current
    c. average current
    d. effective current
24. The term, "angular velocity," as applied to electricity refers to the number of
    a. radians per second a voltage vector rotates
    b. radians per minute a voltage vector rotates
    c. degrees averaged together
    d. degrees subtracted from the radians
25. Vectors indicate
    a. direction
    b. magnitude
    c. time, direction, and magnitude
    d. magnitude and direction
26. When voltages are out of phase, the total voltage can be found by adding
    a. arithmetically
    b. vectorially
    c. peaks values
    d. average values
27. The number of radians per second traversed by an alternating-voltage vector is closely related to its
    a. current sine wave
    b. voltage sine wave
    c. frequency
    d. none of the above

CHAPTER 9

INDUCTANCE AND CAPACITANCE

Inductance

Inductance is the property of an electric circuit that opposes any CHANGE IN THE CURRENT through that circuit. That is, if the current increases, a self-induced voltage opposes this change and delays the increase. If current decreases, a self-induced voltage tends to aid, or prolong the current flow, and delays the decrease. Thus, the most noticeable effect of inductance in a circuit is that current can neither increase nor decrease as fast in an inductive circuit as it can in a noninductive circuit.

The opposition to the current change is essentially an effect of electromagnetic induction, or induced e.m.f. In chapter 1 it was pointed out that a voltage is induced in a conductor whenever the conductor is moved across a magnetic field. The same thing also happens when the magnetic field is moved across the conductor. It is this relative motion between field and conductor that produces self-induced voltage in a conductor.

SELF-INDUCTANCE

Even a perfectly straight length of conductor has some inductance. As previously explained, current in a conductor always produces a magnetic field surrounding, or linking with, the conductor. When the current changes, the magnetic field changes, and an e.m.f. is induced in the conductor. This e.m.f. is called a SELF-INDUCED E.M.F. because it is induced in the conductor carrying the current. The direction of the induced e.m.f. has a definite relation to the direction in which the field that induces the e.m.f. varies. When the current in a circuit is increasing, the flux linking with the circuit is increasing. This flux cuts across the conductor and induces an e.m.f. in the conductor in such a direction as to oppose the increase in current and flux. Likewise, when the current is decreasing, an e.m.f. is induced in the opposite direction and opposes the decrease in current. These effects are summarized by Lenz's law, which states that THE INDUCED E.M.F. IN ANY CIRCUIT IS ALWAYS IN A DIRECTION TO OPPOSE THE EFFECT THAT PRODUCED IT.

The inductance is increased by shaping a conductor so that the electromagnetic field around each portion of the conductor cuts across some other portion of the same conductor. This is shown in its simplest form in figure 9-1 (A). A length of conductor is looped so that two portions of the conductor lie adjacent and parallel to one another. These portions are labeled conductor 1 and conductor 2. When the switch is closed, electron flow through the conductor establishes a typical concentric field around ALL portions of the conductor. For simplicity, however, the field is shown in a single plane that is perpendicular to both conductors. Although the field originates simultaneously in both conductors it is considered as originating in conductor 1 and its effect on conductor 2 will be noted. With increasing current, the field expands outward, cutting across a portion of conductor 2. The resultant induced e.m.f. in conductor 2 is shown by the dashed arrow. Note that it is in OPPOSITION to the battery current and voltage, according to Lenz's law.

The direction of this induced voltage may be determined by applying the Left-Hand Rule for Generators. This rule is applied to a portion of conductor 2 that is "lifted" and enlarged for the purpose in part (A) of figure 9-1. In applying this rule, the thumb of the left hand points in the direction that a conductor is moved through a field. (In this case, the field is moving, or expanding, in one direction, which is the same as the conductor moving in the opposite direction.) The index finger points in the direction of the

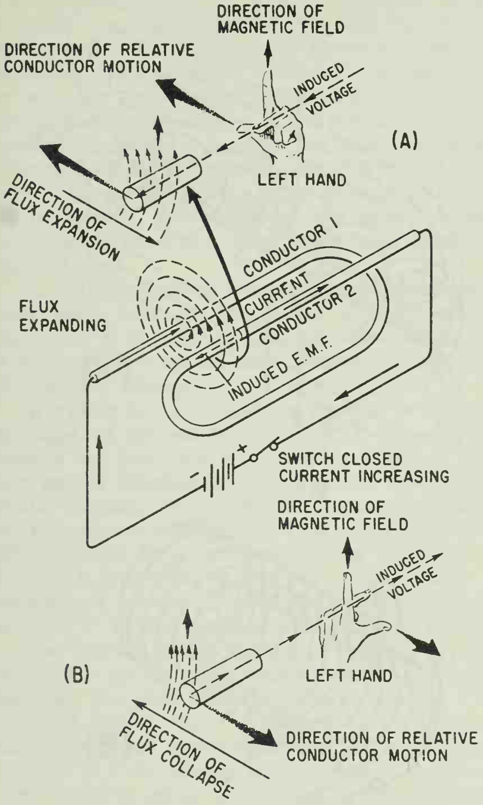

DIRECTION OF MAGNETIC FIELD
DIRECTION OF RELATIVE CONDUCTOR MOTION
INDUCED VOLTAGE
(A)
LEFT HAND
DIRECTION OF FLUX EXPANSION
CONDUCTOR 1
CURRENT
CONDUCTOR 2
FLUX EXPANDING
INDUCED E.M.F.
SWITCH CLOSED CURRENT INCREASING
DIRECTION OF MAGNETIC FIELD
INDUCED VOLTAGE
(B)
LEFT HAND
DIRECTION OF RELATIVE CONDUCTOR MOTION
DIRECTION OF FLUX COLLAPSE

Figure 9-1.—Self-inductance.

magnetic field. The middle finger, extended as shown, will now indicate the direction of induced (generated) voltage.

In part (B), the same section of conductor 2 is shown, but with the switch opened and the flux collapsing. Applying the left-hand rule in this case shows that the reversal of flux MOVEMENT has caused a reversal in the direction of the induced voltage. The most important thing to note, however, is that the voltage of self-induction opposes both CHANGES in current. It delays the initial buildup of current by opposing the battery voltage, and delays the breakdown of current by exerting an induced voltage in the same direction that the battery voltage acted.

UNIT OF INDUCTANCE

The unit for measuring inductance, L, is the HENRY, *h*. An inductor has an inductance of 1 henry if an e.m.f. of 1 volt is induced in the inductor when the current through the inductor is changing at the rate of 1 ampere per second. The relation between the induced voltage, inductance, and rate of change of current with respect to time is stated mathematically as

$$E = L \frac{\Delta I}{\Delta t},$$

where E is the induced e.m.f. in volts, L is the inductance in henrys, and ΔI is the change in current in amperes occurring in Δt seconds. (Delta, symbol Δ, means "a change in . . . . .")

The henry is a large unit of inductance and is used with relatively large inductors. The unit employed with small inductors is the millihenry, *mh*. For still smaller inductors the unit of inductance is the microhenry, μh.

FACTORS AFFECTING SELF-INDUCTANCE

Many things affect the self-inductance of a circuit. An important factor is the degree of linkage between the circuit conductors and its electromagnetic flux. In a straight length of conductor, there is very little flux linkage between one part of the conductor and another. Therefore, its inductance is extremely small. Conductors become much more inductive when they are wound into coils, as shown in figure 9-2. This is true because there is maximum flux linkage between the conductor turns, which lie side by side in the coil.

Inductance is further affected by the manner in which a coil is wound. The coil in figure 9-2 (A) is a poor inductor if compared to the others in the figure, because its turns are widely spaced, thus decreasing the flux linkage between its turns. Also, its lateral flux movement, indicated by the dashed arrows, does not link effectively, because there is only one layer of turns. A more inductive coil is shown in part (B). The turns are closely spaced, and the two layers link each other with a greater number of flux loops during all lateral flux movements. Note that nearly all turns, such as (a) are directly adjacent to four other turns (shaded), thus affording increased flux linkage.

The coil is made still more inductive by winding it in three layers, and providing a highly permeable core, as in figure 9-2 (C). The increased number of layers (cross-sectional area) improves lateral flux linkage. Note that some turns, such as (b) lie directly adjacent to six other turns (shaded). The magnetic properties of the iron core increase the total coil flux strength many times that of an air core coil of the same number of turns.

From the foregoing, it can be seen that the primary factors controlling the inductance of a coil are (1) the number of turns of conductor, (2) the ratio of the cross-sectional area of the coil to its length, and (3) the permeability of its core material. The inductance of a coil is affected by the magnitude of current when the core is a magnetic material. When the core is air, the inductance is independent of the current.

Various formulas have been developed for calculating the self-inductance of inductors. For an inductor consisting of a single layer of wire, and having a length 10 or more times the diameter, the following formula is essentially correct:

$$L = \frac{0.4\pi\mu N^2 S}{10^8 l},$$

in which L is the self-inductance in henrys, N is the number of turns, π equals 3.14, μ is the permeability of the core (if nonmagnetic, $\mu = 1$), S is the cross-sectional area of the coil in cm.^{2} and l is the length of the coil in centimeters. Thus, it may be seen that the inductance is increased very rapidly as the number of turns is increased; also, the inductance increases as the coil is made shorter, the cross-sectional area is made larger, or the permeability of the core is increased.

For example, the inductance of a coil having a length of 20 cm., a diameter of 2 cm., a core permeability of 200, and 200 turns of wire is approximately

$$L = \frac{0.4\pi \times 200 \times 200^2 \times 0.7854 \times 2^2}{10^8 \times 20} = 0.0158 \text{ henry.}$$

GROWTH AND DECAY OF CURRENT IN AN R-L SERIES CIRCUIT

If a battery is connected across a pure inductance, the current builds up to its final value at a rate that is determined by the battery voltage and the internal resistance of the battery.

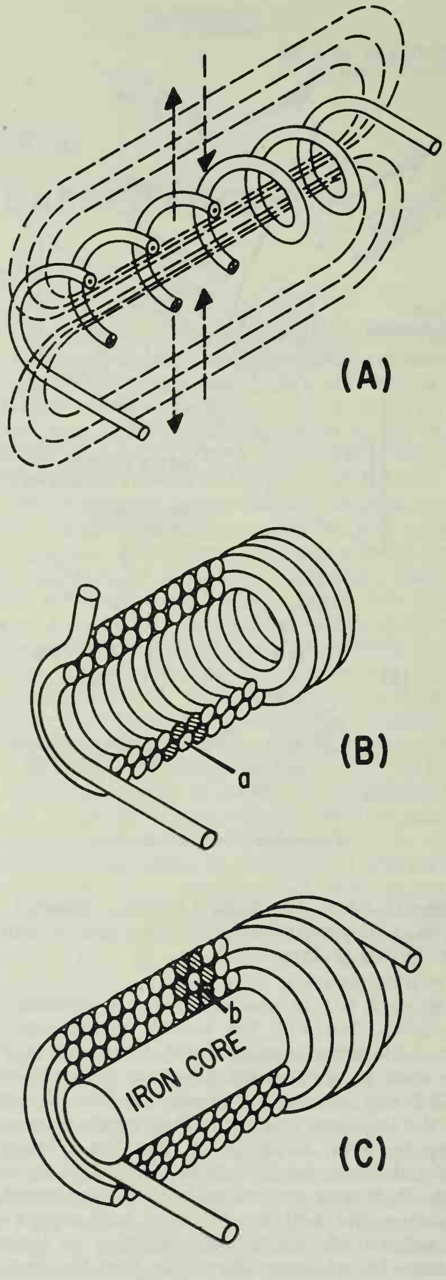


Figure 9-2.—Coils of various inductances.

The current buildup is gradual because of the counter e.m.f. generated by the self-inductance of the coil. When the current starts to flow, the magnetic lines of force move out, cut the turns of wire on the inductor, and build up a counter e.m.f. that opposes the e.m.f. of the battery. This opposition causes a delay in the time it takes the current to build up to steady value. When the battery is disconnected, the lines of force collapse, again cutting the turns of the inductor and building up an e.m.f. that tends to prolong the current flow.

A voltage divider containing resistance and inductance may be connected in a circuit by means of a special switch, as shown in figure 9-3 (A). Such a series arrangement is called an *R-L* series circuit.

If switch *S*1, is closed (as shown), a voltage, *E*, appears across the divider. A current attempts to flow, but the inductor opposes this current by building up a back e.m.f. that, at the initial instant, exactly equals the input voltage, *E*. Because no current can flow under this condition, there is no voltage across resistor *R*. Figure 9-3 (B) shows that all of the voltage is impressed across *L* and no voltage appears across *R* at the instant switch *S*1 is closed.

As current starts to flow, a voltage, e_r, appears across *R*, and e_L is reduced by the same amount. The fact that the voltage across *L* is reduced means that the growth current, i_g, is increasing and censequently e_r is increasing. Figure 9-3 (B) shows that e_L finally becomes zero when i_g stops increasing, while e_r builds up to the input voltage, *E*, as i_g reaches its maximum value. Under steady-state conditions, only the resistor limits the size of the current.

Electrical inductance is like mechanical inertia, and the growth of current in an inductive circuit can be likened to the acceleration of a boat on the surface of the water. The boat begins to move at the instant a constant force is applied to it. At this instant its rate of change of speed (acceleration) is greatest, and all the applied force is used to overcome the inertia of the boat. After a while the speed of the boat increases (its acceleration decreases) and the applied force is used up in overcoming the friction of the water against the hull. As the speed levels off and the acceleration becomes zero, the applied force equals the opposing friction force at this speed and the inertia effect disappears.

When the battery switch in the *R-L* circuit of figure 9-3 (A) is closed, the rate of current increase is maximum in the inductive circuit. At this instant all the battery voltage is used in overcoming the e.m.f. of self-induction which is a maximum because the rate of change of current is maximum. Thus the battery voltage is equal to the drop across the inductor and the voltage across the resistor is zero. As time goes on more of the battery voltage appears across the resistor and less across the inductor. The rate of change of current is less and the induced e.m.f. is less. As the steady-state condition of the current flow is approached the drop across the inductor approaches zero and all of the battery voltage is used to overcome the resistance of the circuit.

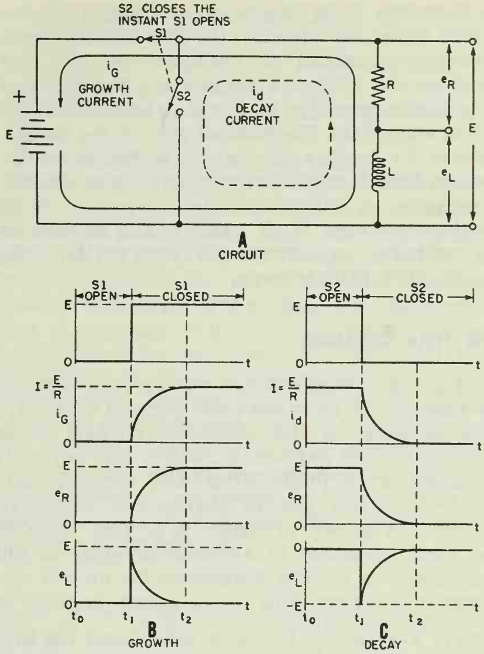


Figure 9-3.–Growth and decay of current in an R-L series circuit.

Thus the voltage across the inductor and resistor change in magnitudes during the period of growth of current the same way the force applied to the boat divides itself between the inertia and friction effects. In both examples, the force is developed first across the inertia-inductive effect and finally across the friction-resistive effect.

If switch $S2$ is closed (source voltage E removed from the circuit), the flux that has been established around L collapses through the windings and induces a voltage, e_L, in L that has a polarity opposite to E and essentially equal to it in magnitude. The induced voltage, e_L, causes current i_d to flow through R in the same direction that it was flowing when $S1$ was closed. A voltage, e_r, that is initially equal to E, is developed across R. It rapidly falls to zero as the voltage, e_L, across L, due to the collapsing flux, falls to zero.

L/R Time Constant

The time required for the current through an inductor to increase to 63 percent (actually, 63.2 percent) of the maximum current or to decrease to 37 percent (actually, 36.7 percent) is known as the TIME CONSTANT of the circuit. An R-L circuit and its charge and discharge graphs are shown in figure 9-4. The value of the time constant in seconds is equal to the inductance in henrys divided by the circuit resistance in ohms. One set of values is given in figure 9-4 (A). $\frac{L}{R}$ is the symbol used for this time constant.

Two useful relations used in calculating $\frac{L}{R}$ time constants are as follows:

$$\frac{L \text{ (in henrys)}}{R \text{ (in ohms)}} = t \text{ (in seconds)}.$$

$$\frac{L \text{ (in microhenrys)}}{R \text{ (in ohms)}} = t \text{ (in microseconds)}.$$

The time constant may also be defined as the time required for the current through the inductor to grow or decay to its final value IF it continued to grow or decay at its initial rate. As may be seen in figure 9-4 (B), the slope of the dotted tangent line, ox, indicates the initial rate of current growth with respect to time. At this rate, the current would reach its maximum value in $\frac{L}{R}$ seconds. Similarly, the slope of the dotted tangent line, YZ, indicates the initial rate of current decay with respect to time, and the decay would be completed in $\frac{L}{R}$ seconds.

The equation for the growth of current, i_L, through L is

$$i_L = \frac{E}{R}\left(1 - \frac{1}{2.718^{\frac{Rt}{L}}}\right),$$

where i_L is the instantaneous current through inductor L, E is the applied voltage (100 volts in this case), R is the resistance in ohms, t is the time in seconds, and L is the inductance in henrys. Figure 9-4 (B) shows a graph of this equation.

When $t=\frac{L}{R}$, the exponent $\frac{Rt}{L}$ in the preceding equation reduces to 1. Then $\frac{1}{2.718} = 0.368$. Therefore,

$$i_L = \frac{E}{R}(1 - 0.368) = 0.632\frac{E}{R}.$$

In other words, when $t=\frac{L}{R}$, i_L is equal to 63.2 percent of the ratio $\frac{E}{R}$, which is the maximum current. When the maximum current is 10 amperes (E=100 and R=10), the current through L grows to 6.32 amperes in $\frac{L}{R}=\frac{10}{10}$, or 1 second.

The equation for inductor voltage, e_L, on growth of current is

$$e_L = E\left(\frac{1}{2.718^{\frac{Rt}{L}}}\right).$$

The graph of this equation is also shown in figure 9-4 (B). When $t=\frac{L}{R}$, $e_L=0.368E$; that is, $e_L = 0.368 \times 100 = 36.8$ volts.

Mutual Inductance

MUTUAL INDUCTANCE DEFINED

Whenever two coils are located so that the flux from one coil links with the turns of the other, a change of flux in one coil will cause an e.m.f. to be induced in the other coil. The two coils have MUTUAL INDUCTANCE. The amount of mutual inductance depends on the relative position of the two coils. If the coils are separated a considerable distance, the amount of flux common to both coils is small and the mutual inductance is low. Conversely, if the coils are close together so that nearly all the flux of one coil links the turns of the other the mutual inductance is high. The mutual inductance can be increased greatly by mounting the coils on a common iron core.

Two coils placed close together with their axes in the same plane are shown in figure 9-5. Coil *A* is connected to a battery through switch *S*, and coil *B* is connected to galvanometer *G*. When the switch is closed (fig. 9-5 (A)), the current that flows in coil *A* sets up a magnetic field that links coil *B*, causing an induced current and a momentary deflection of galvanometer *G*. When the current in coil *A* reaches a steady value, the galvanometer returns to zero. If the switch is opened (fig. 9-5 (B)), the galvanometer deflects momentarily in the opposite direction, indicating a momentary flow of current in the opposite direction in coil *B*. This flow of current in coil *B* is caused by the e.m.f. induced in coil *B*, which is produced by the collapsing flux of coil *A*.

When current flows through coil *A* the flux expands in coil *A* producing a north pole nearest coil *B*. Some of the flux, that expands from left to right, cuts the turns of coil *B*. This flux induces an e.m.f. and current in coil *B* that opposes the growth of current and flux in coil *A*. Thus the current in *B* tries to establish a north pole nearest coil *A* (like poles repel).

When the switch is opened, the magnetic field produced by coil *A* collapses. The collapse of the flux cuts the turns of coil *B* in the opposite direction and produces a south pole nearest coil *A* (unlike poles attract). This polarity aids the magnetism of coil *A*, tending to prevent the collapse of its field.

FACTORS AFFECTING MUTUAL INDUCTANCE

The mutual inductance of two adjacent coils is dependent upon the—(1) physical dimensions of the two coils, (2) number of turns in each coil, (3) distance between the two coils, (4) relative positions of the axes of the two coils, and (5) the permeability of the cores.

If the two coils are positioned so that all the flux of one coil cuts all the turns of the other, the mutual inductance can be expressed as follows:

$$M = \frac{0.4\pi\mu S N_1 N_2}{10^8 l}$$

where M equals mutual inductance of coils in henrys
N_1 and N_2 equal the number of turns in coils 1 and 2 respectively
S equals area of core in square cm.
μ equals permeability of core
l equals length of core in cm.

If the two coils are so positioned with respect to each other that all the flux of one coil cuts all the turns of the other, the coils have UNITY COEFFICIENT OF COUPLING. If all of the flux produced by one of the coils cuts only one-half the turns of the other coil, the coefficient of coupling is 0.5. Coefficient of coupling is designated by the letter, *K*. The coefficient of coupling is equal to the percentage of flux originating in one coil that cuts the other coil. It is never exactly equal to unity but it approaches this value in certain shell-type transformers.

The mutual inductance between two coils, *L*1 and *L*2, may be expressed in terms of the inductance of each coil and the coefficient of coupling, *K*, as follows,

$$M = K\sqrt{L_1 L_2},$$

where *M* is in the same units of inductance as *L*1 and *L*2.

SERIES INDUCTORS WITHOUT MAGNETIC COUPLING

When inductors are well shielded, or located far enough apart to make the effects of mutual inductance negligible, the inductance of the various inductors are added in the same manner that the resistances of resistors are added. For example,

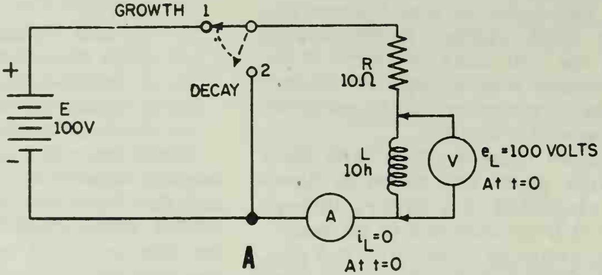
$$L_T = L_1 + L_2 + L_3 \ldots + L_N,$$

where L_t is the total inductance; L_1, L_2, L_3 are the inductances of *L*1, *L*2, *L*3; and L_N means that any number (*N*) of inductors may be used.

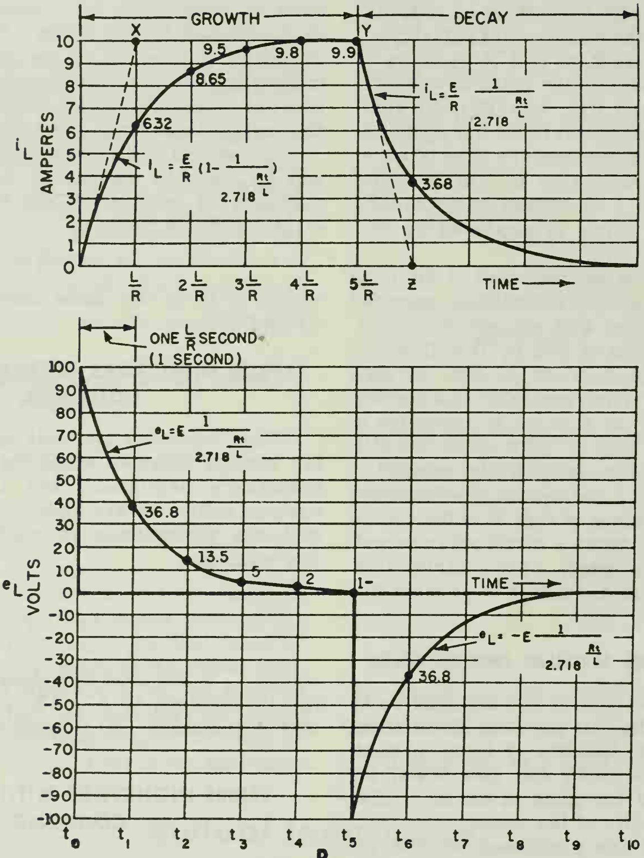
SERIES INDUCTORS WITH MAGNETIC COUPLING

When two inductors in series are so arranged that the field of one links the other, the combined inductance is determined as

$$L_T = L_1 + L_2 \pm 2M,$$


GROWTH 1
DECAY
2
+
-
E
100V
R
10Ω
L
10h
V
e_L=100 VOLTS
At t=0
A
i_L=0
At t=0

A
CIRCUIT



B
GROWTH AND DECAY GRAPHS

Figure 9-4.—L/R time constant.

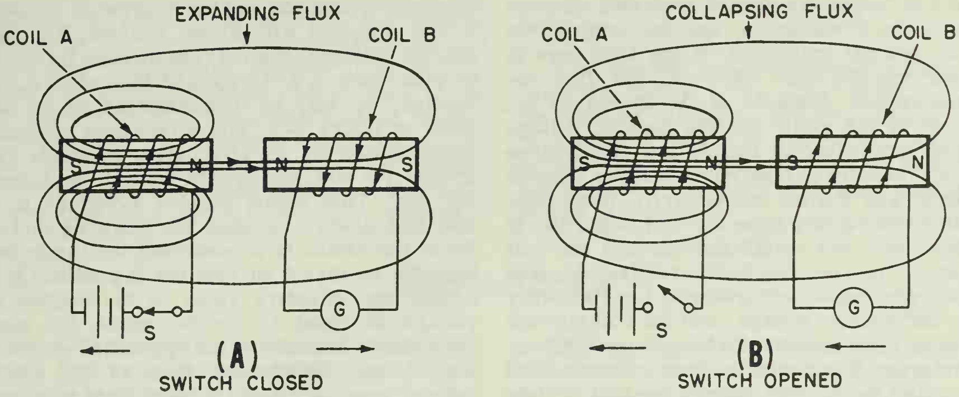


Figure 9-5.—Mutual inductance.

where L_T is the total inductance, L_1 and L_2 are the self inductances of $L1$ and $L2$ respectively, and M is the mutual inductance between the two inductors. The plus sign is used with M when the magnetomotive forces of the two inductors are aiding each other. The minus sign is used with M when the m.m.f.'s of the two inductors oppose each other. The factor 2 accounts for the influence of $L1$ on $L2$ and of $L2$ on $L1$.

If the coils are arranged so that one can be rotated relative to the other to cause a variation in the coefficient of coupling, the mutual inductance between them can be varied. The total inductance, L_T, may be varied by an amount equal to $4M$.

PARALLEL INDUCTORS WITHOUT MAGNETIC COUPLING

The total inductance, L_T, of inductors in parallel is calculated in the same manner that the total resistance of resistors in parallel is calculated, provided the coefficient of coupling between the coils is zero. For example,

$$\frac{1}{L_T} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} \cdots + \frac{1}{L_N},$$

where L_1, L_2, and L_3 are the respective inductances of inductors $L1$, $L2$, and $L3$; and L_N means that any number (N) of inductors may be used.

EFFECTS OF INDUCTANCE IN AN ELECTRIC CIRCUIT

Reaction of an Inductor to Flux Change

Up to this point, the effects of inductance in an electric circuit have been considered as being controlled only by the particular inductor considered in each case. For instance, the time required for the growth and decay of current in the circuit shown in figure 9-3 is determined only by the inherent properties of the inductor L, namely, the ratio of its inductance to its resistance. When permitted to change at this inherent, or natural rate, the shape of the L/R curve for any particular inductor will always remain the same. That is, it will always exhibit the same natural opposition to any change in current and flux, when left to its own tendencies. At this point, however, it must be pointed out that an inductor can be made to exhibit many different degrees of reaction. This is done by using external means to change the flux linking the inductor. These changes, such as variations in the applied frequency, usually do not occur at the same rate as the inductor's inherent rate. When the flux is changed RAPIDLY by some external means, the inductor's reaction is much greater than when the flux is changed gradually. That is, the inductor's self-induced e.m.f. is dependent on the RATE with respect to time at which the linking flux is changed.

The dependence of the induced voltage on the rate of change of flux with respect to time is shown by means of the simple apparatus in figure 9-6. When the switch is closed, current builds up to a maximum, and the lamp glows with its normal brilliance. If the iron core is inserted rapidly into the coil, the flux increases rapidly (because of the increased inductance of the coil), and the induced voltage opposes, according to Lenz's law, the source voltage. Therefore, less current flows through the lamp, and it dims momentarily. If the core is withdrawn rapidly from the coil, a portion of the flux that was established around the coil collapses. The resulting induced voltage opposes the decrease (again, according to Lenz's law) by aiding the source voltage, and the coil current increases. Consequently, the lamp burns brighter momentarily. The faster the iron core is moved the greater is the flux change per unit of time and the more noticeable is the effect on the lamp.

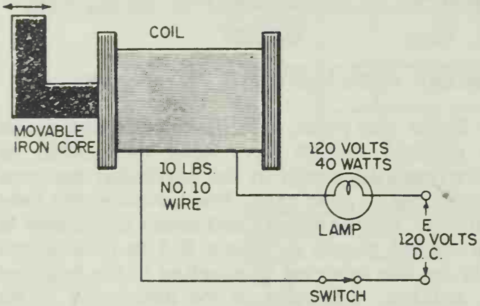


Figure 9-6.—Dependence of self-induced voltage on the rate of change of flux.

Effects of Inductance in an A-C Circuit

When a circuit containing a coil is energized with direct current, the coil's effect in the circuit is evident only when the circuit is energized, or when it is deenergized. For instance, when the switch in figure 9-7 is placed in position ①, the inductance of coil *L* will cause a delay in the time required for the lamps to attain normal brilliance. After they have attained normal brilliance, the inductance has no effect on the circuit as long as the switch remains closed. When the switch is opened, an electric spark will jump across the opening switch contacts. The e.m.f. which produces the spark is caused by the collapsing magnetic field cutting the turns of the inductor.

When the inductive circuit is supplied with alternating current, however, the inductor's effect is continuous and much greater than when it was supplied with direct current. For equal applied voltages, the current through the circuit is less when a. c. is applied than when d. c. is applied, as may be demonstrated by the circuits of figure 9-7. The alternating current is accompanied by an alternating magnetic field around the coil, which cuts through the turns of the coil. This action induces a voltage in the coil that always opposes the changing current. When the switch is in position ① the lamps burn brightly on direct current but in position ②, although the effective value of the applied a-c voltage is equal to the d-c value, the lamps burn dimly because of the opposition developed across the inductance. Most of the applied voltage appears across *L*, with little remaining for the lamps.

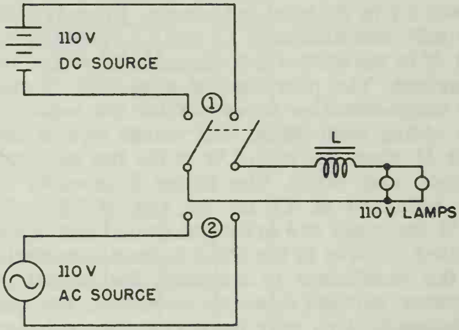


Figure 9-7.—Relative effects of inductance in d-c and a-c circuits.

Relation Between Induced Voltage and Current

As stated previously, any change in current, either a rise or a fall, in a coil causes a corresponding change of the magnetic flux around the coil (fig. 9-8, (A)). If the current is sinusoidal, the induced voltage will also have the form of a sine wave. Because the current changes at its maximum rate when it is going through its zero value at 0°, 180°, and 360° (fig. 9-8 (B)), the flux change is also greatest at those times. Consequently, the self-induced voltage in the coil is at its maximum value at these instants. According to Lenz's law, the induced voltage always opposes the change in current. Thus, when the current is rising in a positive direction at 0°, the induced e.m.f. is of opposite polarity to the impressed e.m.f. and opposes the rise in current. Later, when the current is falling toward its zero value at 180°, the induced voltage is of the same polarity as the current and tends to keep the current from falling. Thus the induced voltage can be seen to lag the current by 90°. The resistance of the coil is small and the principal opposition to the current flow through the coil is the induced voltage, E_{ind}. The applied voltage, E, is slightly larger than E_{ind} and diametrically opposed to it, as indicated in the vector diagram (fig. 9-8 (C)).

The current lags the applied voltage in an inductive circuit by an angle of 90° and leads the induced voltage by 90°. The induced voltage is always of opposite polarity to the applied voltage and is called a COUNTER E.M.F. or a BACK E.M.F. because it always opposes the change of current.

Capacitance

Capacitance is the property of an electric circuit that resists, or opposes, any CHANGE OF VOLTAGE in the circuit. That is, if applied voltage is increased, capacitance opposes the change and delays the voltage increase across the circuit. If applied voltage is decreased, capacitance tends to maintain the higher original voltage across the circuit, thus delaying a decrease. Consequently, the most noticeable effect of capacitance in a circuit is that voltage can neither increase nor decrease as fast in a capacitive circuit as it can in a noncapacitive circuit. Capacitance is also defined as that property of a circuit that enables energy to be stored in an electric field.

THE CAPACITOR

Figure 9-9 depicts a capacitor in its simplest form. It consists of two metal plates separated by a thin layer of insulating material (dielectric). When connected to a voltage source (battery) as shown, the voltage forces electrons onto one plate, making it negative, and pulls them off the other, making it positive. Electrons cannot flow through the dielectric. Since it takes a definite quantity of electrons to "fill up," or charge, a capacitor, it is said to have a CAPACITY. This characteristic is referred to as CAPACITANCE.

The basic action of a capacitor is illustrated in figure 9-10. In part (A), the capacitor is in a balanced, or uncharged, condition. When the switch is set to position 1, in part (B), a surge of battery current immediately charges the capacitor. The natural tendency of the capacitor is to restore its own balance by discharging through the battery in a counterclockwise direction. This tendency is small at first, but grows as the capacitor is charging.

This characteristic is commonly referred to as a counter e.m.f., since it is actually a voltaic force. When the capacitor's counter e.m.f. has risen to equal the battery voltage, the capacitor is said to be charged, and current is zero. When the charge is completed, the switch is placed back to position 2, as shown in figure 9-10 (C).

In this condition, the capacitor is a source of potential energy, similar to a charged battery. Its charged plates exert a voltage between terminals 2 and 3 of the switch. In addition, an electrostatic field, or force, exists between the plates, acting through the dielectric. This is an actual physical force, evidenced by the mutual attraction of the unlike charges, and the dielectric must be structurally strong enough to withstand it. The dielectric must also have sufficient insulating qualities to withstand the potential differences. When the switch is placed in position 3, the capacitor discharges, thus rebalancing itself. As the potential difference of the plates goes to zero, their charges are equalized, and the electrostatic force is relaxed.

Two facts should be noted in connection with figure 9-10 (B):

1. After a momentary surge of electrons, direct current is completely stopped by the capacitor.
2. Free electrons do not pass from one plate to the other through the dielectric because the dielectric is a nonconductor.

The electrons are distributed on the negative plate and held there by the mutual attraction of the corresponding positive charges on the positive plate. The presence of the two polarities (plus and minus) establishes the electric field through the dielectric.

The electric lines of force (flux) originate on the negatively charged plate and terminate on the positively charged plate. In other words,

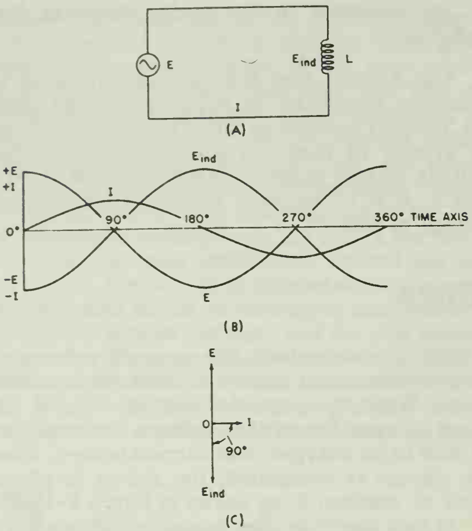


Figure 9-8.—Relation between induced voltage and current.

the lines are assumed to follow the same paths that UNIT NEGATIVE CHARGES would take if they were free to move. The lines of force would be present even if the plates were enclosed in a perfect vacuum. Electric lines of force cannot exist in a metallic conductor to any great extent, because equalizing currents are free to flow within the metal. If the force is to exist, two dissimilarly charged bodies must be separated by a nonconductor.

DIELECTRIC MATERIALS

Various materials differ in their ability to support electric flux or to serve as dielectric material for capacitors. This phenomenon is somewhat similar to permeability in magnetic circuits. Dielectric materials, or insulators are rated in their ability to support electric flux in terms of a figure called the DIELECTRIC CONSTANT. The higher the value of dielectric constant (other factors being equal), the better is the dielectric material.

Dry air is the standard dielectric for purposes of reference and is assigned the value of unity (or one). The dielectric constant of a dielectric material is also defined as the ratio of the capacitance of a capacitor having that particular material as the dielectric to the capacitance of the same capacitor having air as the dielectric. By way of comparison, the dielectric constant of pure water is 81; flint glass, 9.9; and paraffin paper, 3.5. The range of dielectric constants is much more restricted than is the range of permeabilities. Average dielectric constants for some common materials is given in the following list.

Material	Dielectric-constant (Average values)
Air	1
Polystyrene	2.5
Paraffin paper	3.5
Mica	6
Flint glass	9.9
Methyl alcohol.	35
Glycerin	56.2
Pure water.	81

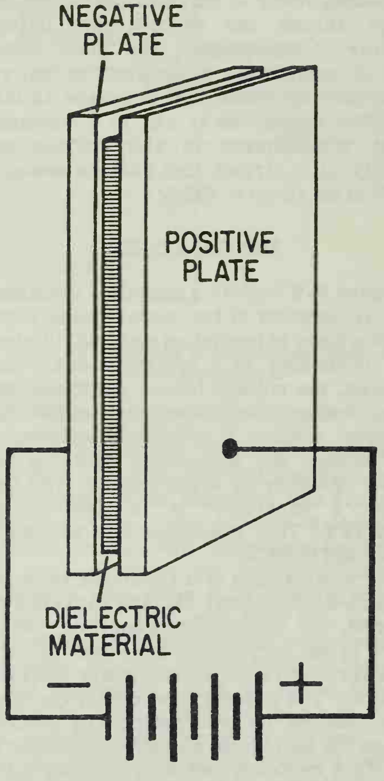


Figure 9-9.—Simple capacitor.

UNIT OF CAPACITANCE

The capacitance of a capacitor is proportional to the quantity of charge that can be stored in it for each volt applied across its plates. A capacitor possesses a capacitance of 1 FARAD when a quantity of charge of 1 coulomb imparted to it raises its potential 1 volt (1 coulomb is equal to 6.28×10^{18} electrons). The relation between capacitance, charge, and voltage is the basic formula of the capacitor, and may be stated as follows:

$$C = \frac{Q}{E},$$

where C is the capacitance in farads, Q the quantity of charge in coulombs, and E the difference in potential in volts.

A capacitor with a value of 1 farad would be of enormous dimensions. Hence, use of the farad as a unit is usually limited to definition and calculations. The practical units of capacitance are the microfarad (μf.) and the micromicrofarad (μμf.). A capacitor whose value is 1 microfarad is one in which a microcoulomb (6.28×10^{12} electrons) is stored when 1 volt is applied across its plates.

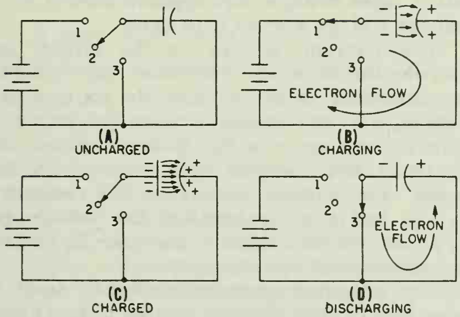


Figure 9-10.–Capacitor action.

FACTORS AFFECTING THE VALUE OF CAPACITANCE

The capacitance of a capacitor depends on the three following factors:

1. The area of the plates.
2. The distance between the plates.
3. The dielectric constant of the material between the plates.

These three factors are related to the capacitance of a parallel-plate capacitor consisting of two plates by the formula

$$C = 0.2249\left(\frac{kA}{d}\right)$$

where C is in micromicrofarads, A is the area of one of the plates in square inches, d is the distance between the plates in inches, and k is the dielectric constant of the insulator separating the plates.

For example, the capacitance of a parallel-plate capacitor with an air dielectric and spacing of 0.0394 inch between the plates, each of which has an area of 15.5 square inches, is approximately

$$C = 0.225\left(\frac{1 \times 15.5}{0.0394}\right) = 88.5 \text{ micromicrofarads.}$$

From this formula it may seen that the capacitance increases when the plates are increased in area; it decreases, if the spacing of the plates is increased; and it increases if the k-value is increased.

The dielectric constant, k, expresses the relative capacitance when materials other than air are used as the insulating material between the plates. For example, if mica is substituted for air as the dielectric, the capacitance increases 6 times because the dielectric constant of mica is 6 and that of air is 1.

If the capacitor is composed of more than two parallel plates, the capacitance is calculated by multiplying the preceding formula by $N - 1$, where N is the number of plates. The plates are interlaced as shown in figure 9-11, and the effect is that of increasing the capacitance of the two-plate capacitor by the factor $N - 1$. In the figure there are 11 plates, and the capacitance is 10 times that of a 2-plate capacitor of the same plate area, spacing, and dielectric material.

CHARGE AND DISCHARGE OF AN R-C SERIES CIRCUIT

Ohm's law states that the voltage across a resistance is equal to the current through it times the value of the resistance. This means that a voltage will be developed across a resistance ONLY WHEN CURRENT FLOWS through it.

A capacitor is capable of storing or holding a charge of electrons. When uncharged, both

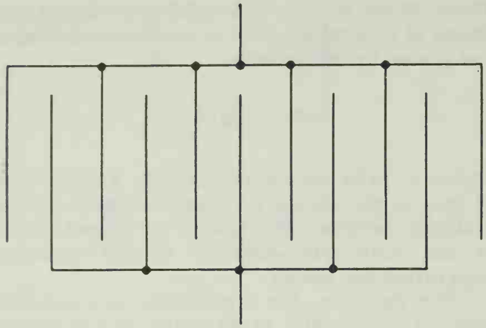


Figure 9-11.—Capacitor multiple-plate construction.

plates contain the same number of free electrons. When charged, one plate contains more free electrons than the other. The difference in the number of electrons is a measure of the charge on the capacitor. The accumulation of this charge builds up a voltage across the terminals of the capacitor, and the charge continues to increase until this voltage equals the applied voltage. The charge in a capacitor is related to the capacitance and voltage as follows:

$$Q = CE,$$

in which Q is the charge in coulombs, C the capacitance in farads, and E the difference in potential in volts. Thus, the greater the voltage, the greater the charge on the capacitor. Unless a discharge path is provided, a capacitor keeps its charge indefinitely. Any practical capacitor, however, has some leakage through the dielectric so that the charge will gradually leak off.

A voltage divider containing resistance and capacitance may be connected in a circuit by means of a switch, as shown in figure 9-12 (A). Such a series arrangement is called an R-C series circuit.

If $S1$ is closed, electrons flow counterclockwise around the circuit containing the battery, capacitor, and resistor. This flow of electrons ceases when C is charged to the battery voltage. At the instant current begins to flow, there is no voltage on the capacitor and the drop across R is equal to the battery voltage. The initial charging current, I, is therefore equal to $\frac{E_s}{R}$. Figure 9-12 (B) shows that at the instant the switch is closed, the

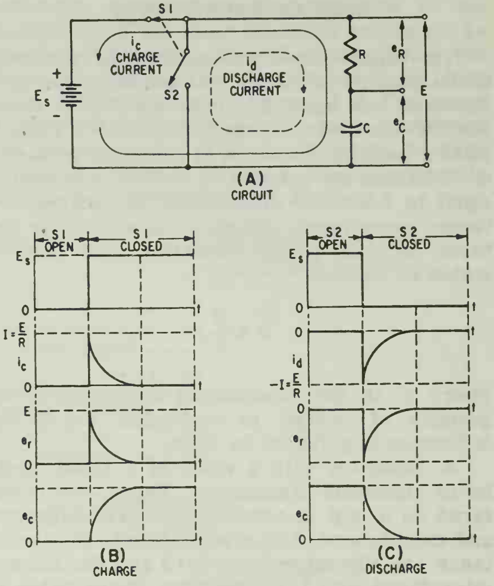


Figure 9-12.—Charge and discharge of an R-C series circuit.

entire input voltage, E_s, appears across R, and that the voltage across C is zero.

The current flowing in the circuit soon charges the capacitor. Because the voltage on the capacitor is proportional to its charge, a voltage, e_c, will appear across the capacitor. This voltage opposes the battery voltage—that is, these two voltages buck each other. As a result, the voltage e_r across the resistor is $E_s - e_c$, and this is equal to the voltage drop (i_cR) across the resistor. Because E_s is fixed, i_c decreases as e_c increases.

The charging process continues until the capacitor is fully charged and the voltage across it is equal to the battery voltage. At this instant, the voltage across R is zero and no current flows through it. Figure 9-12 (B) shows the division of the battery voltage, E_s, between the resistance and capacitance at all times during the charging process.

If $S2$ is closed ($S1$ opened) in figure 9-12 (A), a discharge current, i_d, will discharge the capacitor. Because i_d is opposite in direction to i_c, the voltage across the resistor will have a polarity opposite to the polarity during the charging time. However, this voltage will have the same magnitude and will vary in the same manner. During discharge the voltage across the capacitor is equal and opposite to the drop across the resistor, as shown in figure 9-12 (C). The voltage drops rapidly from its initial value and then approaches zero slowly, as indicated in the figure.

RC TIME CONSTANT

The time required to charge a capacitor to 63 percent (actually 63.2 percent) of maximum voltage or to discharge it to 37 percent (actually 36.8 percent) of its final voltage is known as the TIME CONSTANT of the circuit. An *R-C* circuit with its charge and discharge graphs is shown in figure 9-13. The value of the time constant in seconds is equal to the product of the circuit resistance in ohms and its capacitance in farads, one set of values of which is given in figure 9-13 (A). *RC* is the symbol used for this time constant.

Some useful relations used in calculating *RC* time constants are as follows:

$$R\text{ (ohms)} \times C\text{ (farads)} = t\text{ (seconds)}.$$

$$R\text{ (megohms)} \times C\text{ (microfarads)} = t\text{ (seconds)}.$$

$$R\text{ (ohms)} \times C\text{ (microfarads)} = t\text{ (microseconds)}.$$

$$R\text{ (megohms)} \times C\text{ (micromicrofarads)} = t\text{ (microseconds)}.$$

The time constant may also be defined as the time required to charge or discharge a capacitor completely IF it continues to charge or discharge at its initial rate. As may be seen in figure 9-13 (B), the slope of the dotted tangent line, *OX*, indicates the initial rate of charge. At this rate, the capacitor would be completely charged in *RC* seconds. Likewise, the slope of the dotted tangent line, *YZ*, indicates the initial rate of discharge with respect to time, and at this rate the capacitor would be completely discharged in *RC* seconds.

The equation for the rise in voltage, e_C, across the capacitor is

$$e_c = E\left(1 - \frac{1}{2.718^{\frac{t}{RC}}}\right),$$

where e_C, is the instantaneous voltage across the capacitor, *E* the applied voltage (100 volts in this case), *t* the time in seconds, *R* the resistance in ohms, *C* the capacitance in farads (0.000001 farad or 1μf. in this case), and the number 2.718 the natural logarithm base. Figure 9-13 (B) shows a graph of this equation.

When $t = RC$, the exponent, $\frac{t}{RC}$, reduces to 1. Therefore,

$$e_c = E\left(1 - \frac{1}{2.718}\right) = 0.632\,E.$$

In other words, when $t = RC$, e_C is equal to 63.2 percent of *E*, the maximum value. When the maximum is 100 volts, as shown, the voltage across the capacitor increases to 63.2 volts in *RC* seconds—that is, in 10 microseconds.

The equation for the charging current, i_C, is

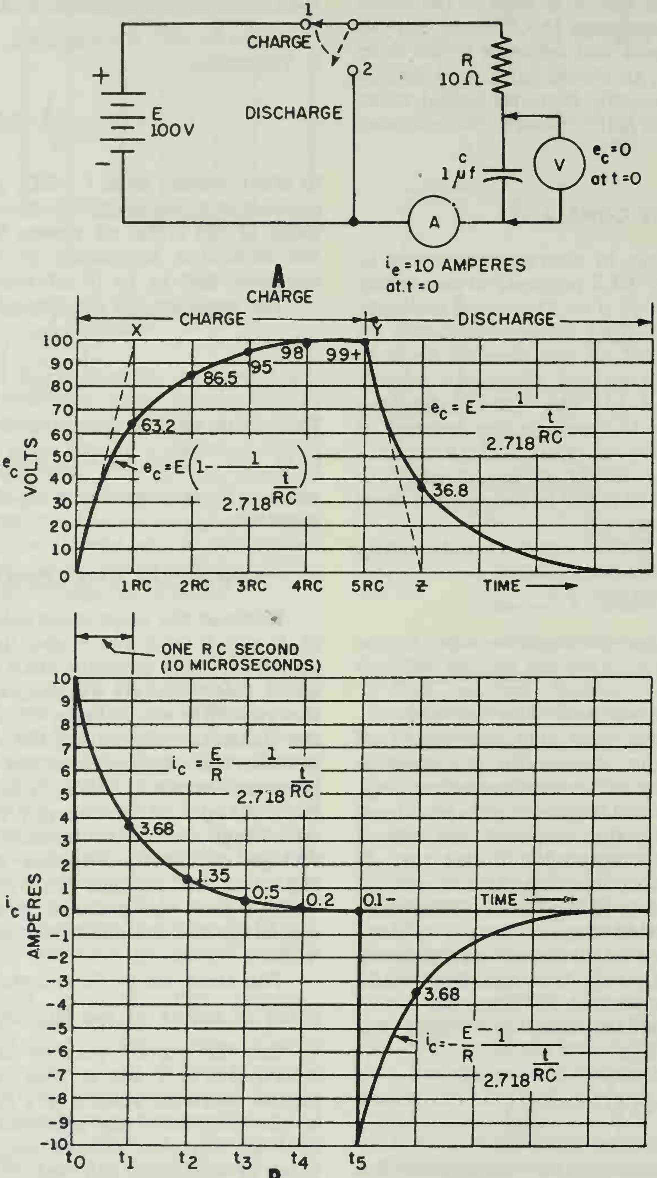
$$i_c = \frac{E}{R}\left(\frac{1}{2.718^{\frac{t}{RC}}}\right).$$

The graph of this equation is shown in figure 9-13 (B). When $t = RC$, $i_C = 0.368 \times \frac{E}{R}$; that is when $t = 10$ microseconds, $i_C = 0.368 \times \frac{100}{10} = 3.68$ amperes.

UNIVERSAL TIME CONSTANT CHART

Because the impressed voltage and the values of *R* and *C* or *R* and *L* usually will be known, a universal time constant chart (fig. 9-14) can be used. Curve *A* is a graph of the voltage across the capacitor on charge; it is also a graph of the inductor current and the voltage across the resistor in series with the inductor on the growth of current. Curve *B* is a graph of capacitor voltage on discharge, capacitor current on charge, inductor current on decay, or the voltage across the resistor in series with the capacitor on charge. The graphs of resistor voltage and current and inductor voltage on discharge are not shown because negative values would be involved.

The time scale (horizontal scale) is graduated in terms of the *RC* or $\frac{L}{R}$ time constants so that the curves may be used for any value of *R* and *C* or *L* and *R*. The voltage and current scales (vertical scales) are graduated in terms of the fraction of the maximum voltage or current so that the curves may be used for any value of voltage or current. If the time constant and the initial or final voltage for the circuit in question are known, the voltages across the various parts of the circuit can be obtained from the curves for any time after the switch


1
CHARGE
2
DISCHARGE
+
−
E
100V
R
10Ω
C
1μf
V
$e_c = 0$
at t = 0
A
i_e = 10 AMPERES
at t = 0
A
CHARGE
CHARGE
DISCHARGE
X
Y
e_c VOLTS
100
90
80
70
60
50
40
30
20
10
0
63.2
86.5
95
98
99+
36.8
$e_c = E\left(1 - \frac{1}{2.718^{\frac{t}{RC}}}\right)$
$e_c = E \frac{1}{2.718^{\frac{t}{RC}}}$
1RC
2RC
3RC
4RC
5RC
Z
TIME
ONE R C SECOND
(10 MICROSECONDS)
i_c AMPERES
10
9
8
7
6
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
−8
−9
−10
$i_c = \frac{E}{R} \frac{1}{2.718^{\frac{t}{RC}}}$
3.68
1.35
0.5
0.2
0.1−
TIME
3.68
$i_c = -\frac{E}{R} \frac{1}{2.718^{\frac{t}{RC}}}$
t_0
t_1
t_2
t_3
t_4
t_5
B

CHARGE AND DISCHARGE GRAPHS

Figure 9-13.—R-C time constant.

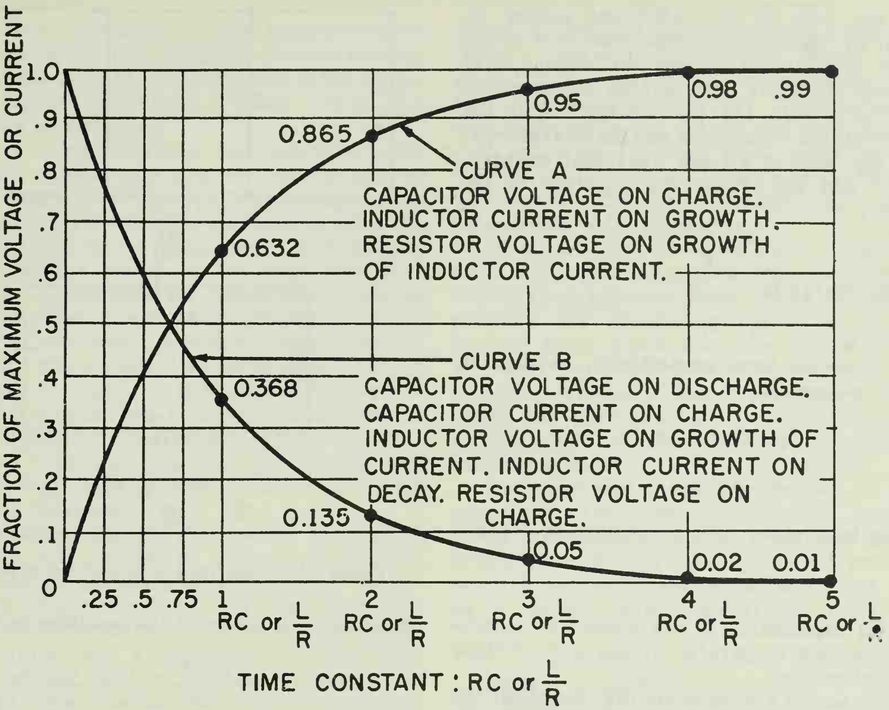


Figure 9-14.—Universal time constant chart for R-C and R-L circuits.

is closed, either on charge or discharge. The same reasoning is true of the current in the circuit.

The following problem illustrates how the universal time constant chart may be used.

A circuit is to be designed in which a capacitor must charge to one-fifth (0.2) of the maximum charging voltage in 100 microseconds (0.0001 second). Because of other considerations, the resistor must have a value of 20,000 ohms. What size of capacitor is needed?

Curve *A* is first consulted to determine the *RC* time necessary to give 0.2 of the full voltage. The time is less than 0.25 *RC*, approximately 0.22 *RC*. If 0.22 *RC* must be equal to 100 microseconds, one complete *RC* must be equal to $\frac{100}{0.22} = 455$ microseconds, or 0.000455 second. Therefore,

$$RC = 0.000455.$$

Substituting the known value of *R* and solving for *C*,

$$C = \frac{0.000455}{20{,}000} = 0.000000023 \text{ farad},$$

or 0.023 microfarad.

The graphs shown in figure 9-13 are not entirely complete—that is, the charge or discharge (or the growth or decay) is not quite completed in 5 *RC* or $5\frac{L}{R}$ seconds. However, when the values reach 0.99 of the maximum (corresponding to 5 *RC* or $5\frac{L}{R}$) the graphs may be considered accurate enough for most purposes.

CAPACITORS IN PARALLEL AND IN SERIES

Capacitors may be combined in parallel or series to give equivalent values, which may be either the sum of the individual values (in parallel) or else a value less than that of the smallest capacitance (in series). Figure 9-15 shows the parallel and series connections.

In figure 9-15 (A) the voltage, E, is the same for all the capacitors and the total charge, Q_t, is the sum of all the individual charges, Q_1, Q_2, and Q_3. From the equation of the capacitor,

$$C = \frac{Q}{E}.$$

The total charge is

$$Q_t = C_t E ,$$

where C_t is the total capacitance. In parallel, the total charge is

$$Q_t = Q_1 + Q_2 + Q_3$$

$$C_t E = C_1 E + C_2 E + C_3 E.$$

Dividing both sides of the equation by E gives

$$C_t = C_1 + C_2 + C_3.$$

The total capacitance of any number of capacitors connected in parallel is the sum of their individual values.

In the series arrangement (fig. 9-15 (B)), the current is the same in all parts of the circuit. Each capacitor develops a voltage during charge, and the sum of the voltages of all the capacitors must equal the applied voltage, E. By the capacitor equation, the applied voltage, E is equal to the total charge divided by the total capacitance, or

$$E = \frac{Q_t}{C_t}.$$

The total charge, C_t, is equal to the charge on any one of the capacitors because the same current flows in all for the same length of time, and because charge equals current times time in seconds ($Q = It$). Therefore,

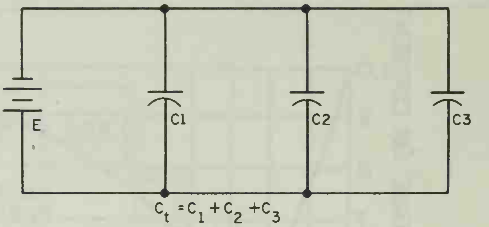
$$Q_t = Q_1 = Q_2 = Q_3.$$

but

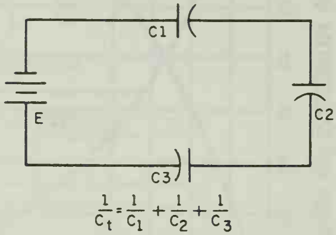
$$E = E_1 + E_2 + E_3,$$

where E_1, E_2, and E_3 are the voltages of the three capacitors. Then

$$\frac{Q_t}{C_t} = \frac{Q_t}{C_1} + \frac{Q_t}{C_2} + \frac{Q_t}{C_3}.$$



(A)
PARALLEL


C1
E
C2
C3
$\frac{1}{C_t} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$

(B)
SERIES

Figure 9-15.—Capacitors in parallel and in series.

Dividing both sides of the equation by Q_t gives

$$\frac{1}{C_t} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}.$$

The reciprocal of the total capacitance of any number of capacitors in series is equal to the sum of the reciprocals of the individual values.

Parallel capacitors combine by a rule similar to that for combining resistors in series. Series capacitors combine by a rule similar to that for combining parallel resistors.

In the series arrangement of two capacitors, C_1 and C_2, the total capacitance is given by the equation:

$$C_t = \frac{C_1 C_2}{C_1 + C_2}.$$

VOLTAGE RATING OF CAPACITORS

In selecting or substituting a capacitor for use in a particular circuit, you must consider (1) the value of capacitance desired, and (2) the amount of voltage to which the capacitor is to be subjected. If the voltage applied across the plates is too great, the dielectric will break down and arcing will occur between the plates. The capacitor is then short-circuited and the possible flow of direct current through it can cause damage to other parts of the equipment. Capacitors have a voltage rating that should not be exceeded.

The working voltage of the capacitor is the maximum voltage that can be steadily applied without danger of arc-over. The working voltage depends on (1) the type of material used as the dielectric, and (2) the thickness of the dielectric.

The voltage rating of the capacitor is a factor in determining the capacitance because capacitance decreases as the thickness of the dielectric increases. A high-voltage capacitor that has a thick dielectric must have a larger plate area in order to have the same capacitance as a similar low-voltage capacitor having a thin dielectric. The voltage rating also depends on frequency because the losses, and the resultant heating effect, increase as the frequency increases.

A capacitor that may be safely charged to 500 volts d.c. cannot be safely subjected to alternating or pulsating direct voltages whose effective values are 500 volts. An alternating voltage of 500 volts (r.m.s.) has a peak voltage of 707 volts, and a capacitor to which it is applied should have a working voltage of at least 750 volts. The capacitor should be selected so that its working voltage is at least 50 percent greater than the highest voltage to be applied to it. Effective (r.m.s.) voltage and the action of capacitors in a-c circuits are described in a later chapter.

CAPACITOR TYPES

Capacitors may be divided into two major groups—fixed and variable.

Fixed Capacitors

Fixed Capacitors are constructed in such manner that they possess a fixed value of capacitance which cannot be adjusted. They may be classified according to the type of material used as the dielectric, such as paper, oil, mica, and electrolyte.

Paper Capacitors.—The plates of paper capacitors are made of strips of metal foil. These are separated by waxed paper. The capacitance of paper capacitors ranges from about 200 micromicrofarads to several microfarads. The strips of foil and paper are rolled together to form a cylindrical cartridge, which is then sealed in wax to keep out moisture and to prevent corrosion and leakage. Two metal leads are soldered to the plates, one extending from each end of the cylinder. Some paper capacitors may have one terminal (lead) marked GROUND, which means that this terminal connects to the outside foil of the capacitor.

Many different kinds of outer covering are used for paper capacitors, the simplest being a tubular cardboard. Some types of paper capacitors are encased in a mold of very hard plastic; these types are very rugged and may be used over a much wider temperature range than the cardboard-case type. Figure 9-16 (A) shows the construction of a tubular paper capacitor; part (B) shows a completed cardboard encased capacitor.

Bathtub-type capacitors consist of paper-capacitor cartridges hermetically sealed in metal containers. (See fig. 9-16 (C)). The container often serves as a common terminal for several enclosed capacitors. It always serves as a shield against electrical interference.

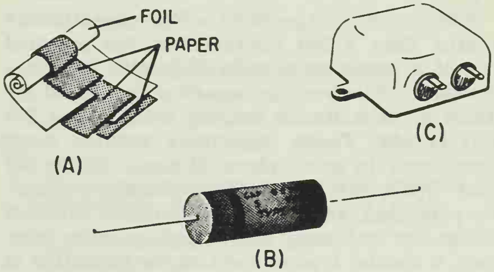


Figure 9-16.—Paper capacitor.

Oil Capacitors.—In radio and radar transmitters, voltages high enough to cause arcing, or breakdown, of paper dielectrics are often employed. Consequently, in these applications capacitors that have oil or oil-impregnated paper as the dielectric material are preferred. Capacitors of this type are considerably more expensive than ordinary paper capacitors and their use is generally restricted to radio and radar transmitting equipment.

Mica Capacitors.—The fixed mica capacitor is made of metal foil plates that are separated by sheets of mica, which form the dielectric. The whole assembly is covered in molded plastic. By molding the capacitor parts into a plastic case, corrosion and damage to the plates and dielectric are prevented in addition to making the capacitor mechanically strong. Various types of terminals are used to connect mica capacitors into circuits; these are also molded into the plastic case.

Mica is an excellent dielectric and will withstand higher voltages than paper without allowing arcing between the plates. Common values of mica capacitors range from approximately 50 micromicrofarads to about 0.02 microfarad. Some typical mica capacitors are shown in figure 9-17.

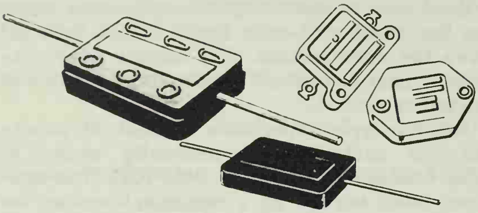


Figure 9-17.—Typical mica capacitors.

Electrolytic Capacitors.—For capacitances greater than a few microfarads, the physical size of a paper or a mica capacitor becomes excessive. Electrolytic capacitors are used for values of capacitance ranging from 1 to 1,500 microfarads. These capacitors provide large capacitance in small physical sizes. Unlike the other types, electrolytic capacitors are generally polarized, and should be subjected to direct voltage, or pulsating direct voltage only; however, a special type of electrolytic capacitor is made for use in alternating-current motors. Remember that unless an electrolytic is designed for use on a.c., it must always be connected in accordance with its polarity markings.

The electrolytic capacitor is widely used in electronic circuits, and consists of two metal plates separated by an electrolyte. The electrolyte, either in paste or liquid form, is in contact with the negative terminal and this combination comprises the negative electrode. The dielectric is an exceedingly thin film of oxide deposited on the positive electrode of the capacitor. The positive electrode is an aluminum sheet, and it is folded so as to achieve maximum area. The capacitor is subjected to a forming process during manufacture, in which current is passed through it. The flow of current results in the deposit of the thin coating of oxide on the aluminum plate. The close spacing of the negative and positive electrodes gives rise to the comparatively high capacitance value. However, it allows greater possibility of voltage breakdown and leakage of electrons from one electrode to the other.

Two kinds of electrolytic capacitors are in use—wet-electrolytic and dry-electrolytic. In the former, the electrolyte is a liquid and the container must be leakproof. This type should always be mounted in a vertical position.

The electrolyte of the dry-electrolytic unit is a paste contained in a separator made of absorbent material such as gauze or paper. The separator serves to hold the electrolyte in place, and also prevents short-circuiting the plates. Dry-electrolytic capacitors are made in both cylindrical and rectangular form and may be contained either within cardboard or metal covers. Since the electrolyte cannot spill, the dry capacitor may be mounted in any convenient position. Some typical electrolytic capacitors are shown in figure 9-18.

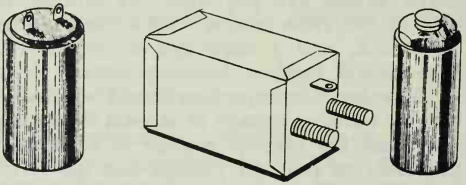


Figure 9-18.—Typical electrolytic capacitors.

Variable Capacitors

Variable capacitors are constructed in such manner that their value of capacitance can be varied. A typical variable capacitor (adjustable capacitor) is the rotor/stator type. It consists of two sets of metal plates that are arranged so that the rotor plates move between the stator plates. Air is the dielectric. As the position of the rotor is changed, the capacitance value is likewise changed. This is the type capacitor used for tuning most radio receivers and it is shown in figure 9-19 (A). Another type variable (trimmer) capacitor is shown in figure 9-19 (B); it consists of two plates separated by a sheet of mica. A screw adjustment is used to change the distance between the plates, thereby changing the capacitance.

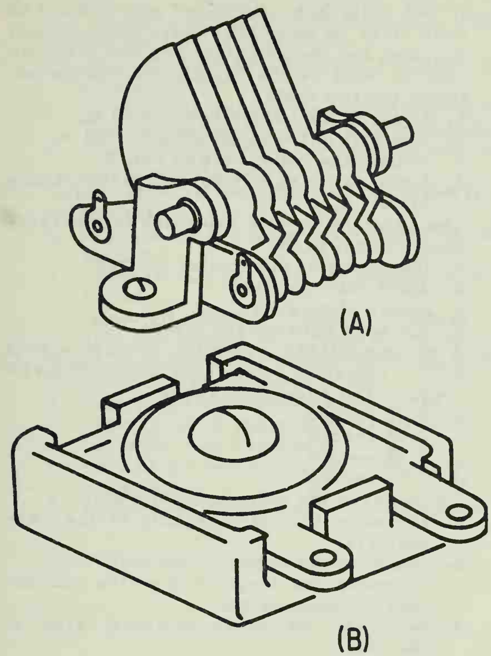


Figure 9-19.—Variable capacitors.

Ceramic Capacitors

A relatively new type capacitor that may be constructed as either fixed or variable is the ceramic. Ceramic capacitors usually range in value between 1 micromicrofarad and 0.01 microfarad. Ceramic is used as the dielectric and film deposits of silver are used for the plates. These capacitors are small in physical size and are constructed in various shapes. Typical capacitors are shown in figure 9-20.

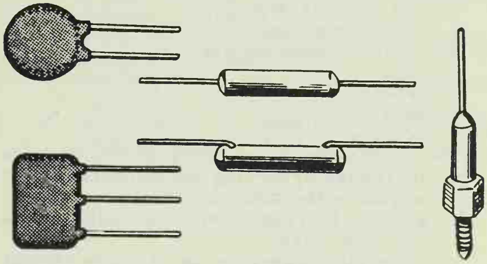


Figure 9-20.—Ceramic capacitors.

QUIZ

1. Inductance is the property of an electric circuit that
   a. opposes any change in the applied voltage through that circuit
   b. opposes any change in the current through that circuit
   c. aids any change in the applied voltage through that circuit
   d. aids any change in the current through that circuit
2. A coil has a resistance of 22 ohms, and in 0.1 second after the switch is closed, the current has reached 63.2% of its final value. The value of inductance (L) is
   a. 0.22 henries
   b. 0.44 henries
   c. 2.20 henries
   d. 4.40 henries
3. When a capacitor's counter e.m.f. has risen to equal the battery voltage, the current is
   a. maximum in the circuit
   b. at 63.2% of its maximum Ohm's law value in the circuit
   c. zero in the circuit
   d. at 36.8% of its maximum Ohm's law value in the circuit
4. The total capacitance of two 100-microfarad capacitors connected in series is
   a. 25 microfarads
   b. 50 microfarads
   c. 100 microfarads
   d. 200 microfarads
5. When the magnetic field is collapsing, the induced e.m.f.
   a. aids and tends to prolong the impressed current
   b. opposes the impressed current
   c. has no effect upon the impressed current
   d. causes the impressed current to go immediately to zero
6. To increase the time required for the current to reach its maximum Ohm's law value in a series resistance and inductance circuit, it is necessary to
   a. increase the resistance
   b. decrease the resistance
   c. decrease the inductance
   d. increase the applied voltage

7. In a simple capacitor (fig. 9-6), the plate area is 2 square inches, the dielectric material is mica, and the distance between the plates is 0.01 inch. To increase the capacitance
   a. increase the distance between the plates
   b. change dielectric material from mica to paraffin paper
   c. decrease the plate area
   d. change dielectric material from mica to flint glass

8. What is the total capacitance of two 200-microfarad capacitors connected in series with each other and both in parallel with a 50-microfarad capacitor?
   a. 50 microfarads
   b. 250 microfarads
   c. 100 microfarads
   d. 150 microfarads

9. The unit of inductance is the
   a. ohm
   b. farad
   c. henry
   d. coulomb

10. The coefficient of coupling of two coils is
   a. increased by turning one coil axis at right angles to the other coil axis
   b. greatly increased with the addition of a soft iron core
   c. generally higher in an air core circuit than in an iron core circuit
   d. almost unity on a diamagnetic core

11. Factors that determine the capacitance of parallel-electrode capacitors are
   a. area of the plates and the type of dielectric
   b. thickness of the plates, type and thickness of the dielectric
   c. type and thickness of the dielectric and the plate area
   d. thickness of the dielectric, area of the plate, and the direction of the current flow

12. The time constant of a resistance-capacitance circuit is
   a. The time required to discharge a capacitor to 36.8% of its final voltage
   b. the time required to charge a capacitor to 36.8% of its maximum voltage
   c. equal to the circuit capacitance divided by the circuit resistance
   d. equal to the circuit resistance divided by the circuit capacitance

13. The voltage due to self-induction
   a. can only occur when the conductor is wound in the form of a coil
   b. is produced when the strength of the magnetic field changes
   c. is produced by moving a conductor through a magnetic field
   d. cannot occur in a direct-current circuit

14. If two coils are positioned with respect to each other so as to have unity coefficient of coupling and the inductance of coil A equals coil B, what is the mutual inductance between the two coils?
   a. Equal to the inductance of coil A.
   b. One half of the inductance of coil A.
   c. Double the inductance of coil A.
   d. Equal to the square root of the inductance of coil A.

15. The capacitance of a capacitor is inversely proportional to the
   a. frequency of the applied voltage
   b. dielectric constant
   c. active plate area
   d. distance between the plates

16. A 40-microfarad capacitor in series with 2,000 ohms is connected to a 200-volt source. The time constant is
   a. 0.05 second
   b. 0.08 second
   c. 0.50 second
   d. 0.80 second

17. To increase the inductance of a coil
   a. increase the permeability of the core material
   b. increase the length of the coil
   c. increase the magnitude of the current flow through the coil
   d. decrease the cross-sectional area of the coil

18. What is the total inductance (L_t) of two coils connected in parallel when the coefficient of coupling is zero?
   a. $L_t = L_1 + L_2$
   b. $L_t = L_1$
   c. $L_t = \frac{1}{L_1} + \frac{1}{L_2}$
   d. $L_t = \frac{L_1 \quad L_2}{L_1 + L_2}$

19. The charge that is stored in a capacitor depends upon
   a. voltage divided by the capacitance
   b. voltage multiplied by the capacitance
   c. capacitance divided by the voltage
   d. capacitance multiplied by the resistance

20. When selecting a capacitor for use in a circuit, its working voltage should be at least
   a. 10% greater than the highest voltage to be applied to it
   b. equal to the highest voltage to be applied to it
   c. 30% greater than the highest voltage to be applied to it
   d. 50% greater than the highest voltage to be applied to it

21. A battery, a switch, a resistor, and a coil are connected in series. What happens at the instant the switch is closed?
    a. The voltage across the resistor is maximum
    b. The voltage across the coil is maximum
    c. The current in the circuit is maximum
    d. The voltage across the resistor and the coil are minimum
22. Capacitance is the property of an electric circuit that
    a. opposes any change of current in the circuit
    b. opposes any change of voltage in the circuit
    c. is not affected by a change of voltage
    d. aids any change of current in the circuit
23. When capacitors are connected in parallel, the resulting capacitance is the
    a. sum of the individual capacitances
    b. reciprocal of the sum of reciprocals of the individual capacitors
    c. sum of the individual reciprocals of the capacitors
    d. reciprocal of the sum of capacitances
24. The time constant of an inductive-resistive circuit is
    a. that time required for a direct current to rise one-half of its maximum value
    b. a method of determining how much current would flow at the end of one second
    c. the product of the resistance and the inductance of a circuit
    d. the time in seconds required for the current to rise to 63.2% of its final Ohm's law value
25. When capacitors are connected in series, the resulting capacitance is found by
    a. a rule similar to that for combining parallel resistors
    b. a rule similar to that for combining resistors in series
    c. dividing the applied voltage by the total resistance of series circuit
    d. multiplying the applied voltage by the total resistance of series circuit

CHAPTER 10

INDUCTIVE AND CAPACITIVE REACTANCE

Inductive Reactance

FACTORS AFFECTING INDUCTIVE REACTANCE

In the preceding chapter, it was shown that when an alternating voltage is applied to an inductor, the inductor reacts in such a way as to oppose alternating-current flow. This opposition is thus referred to in general as an inductive reactance. The amount of opposition exhibited by a coil depends on the magnitude of its self-induced voltage, E_{ind}. The effective value of this self-induced voltage, or counter e.m.f. in volts, is

$$E_{ind} = 2\pi fLI,$$

where 2π is a constant, I is in effective amperes, L is in henrys, and f is in cycles per second. The induced voltage varies directly with the frequency, the inductance, and the current.

The amount of opposition to current flow offered by an inductor is referred to as its inductive reactance. This reactance is expressed as the ratio of the inductor's counter e.m.f. to the current through the inductor, or

$$X_L = \frac{E_{ind}}{I}$$

where X_L is the inductor's opposition to current flow measured in ohms, E_{ind} is the inductor's counter e.m.f. in volts, and I is the inductor current in amperes. Assuming the current and counter voltage have sine waveforms, the inductive reactance X_L, in ohms, is

$$X_L = 2\pi fL$$

Since the inductive reactance of a coil and its counter e.m.f. are closely related, anything which influences one must also influence the other. It has been shown that the counter e.m.f. of a coil depends on its inductance and the rate of flux change around the coil. Consequently, the inductive reactance must also be affected by the same influences. The rate of flux change per unit of time depends on the FREQUENCY of the inductor current. Flux must change more rapidly at high frequencies than at low frequencies. From the foregoing it can be seen that the inductive reactance of a coil depends primarily on (1) the coil's INDUCTANCE and (2) the FREQUENCY of the current flowing through the coil.

If frequency or inductance varies, inductive reactance must also vary. A coil's inductance does not vary appreciably after the coil is manufactured, unless it is designed as a variable inductor. Thus, frequency is generally the only variable factor affecting the inductive reactance of a coil. The coil's inductive reactance will vary directly with the applied frequency.

POWER IN AN INDUCTIVE CIRCUIT

The power in a d-c circuit is equal to the product of volts and amperes, but in an a-c circuit this is true only when the load is resistive, and has no reactance.

In a circuit possessing inductance only, the true power is zero (fig. 10-1). The current lags the applied voltage by 90°. The TRUE POWER is the average power actually consumed by the circuit, the average being taken over one complete cycle of alternating current. The APPARENT POWER is the product of r.m.s. volts and r.m.s. amperes. Thus, in figure 10-1 (A), the apparent power is 100 x 10 = 1,000 volt-amperes. However, the power absorbed by the coil during the time the current is rising (fig. 10-1 (B)), is returned to the source during the

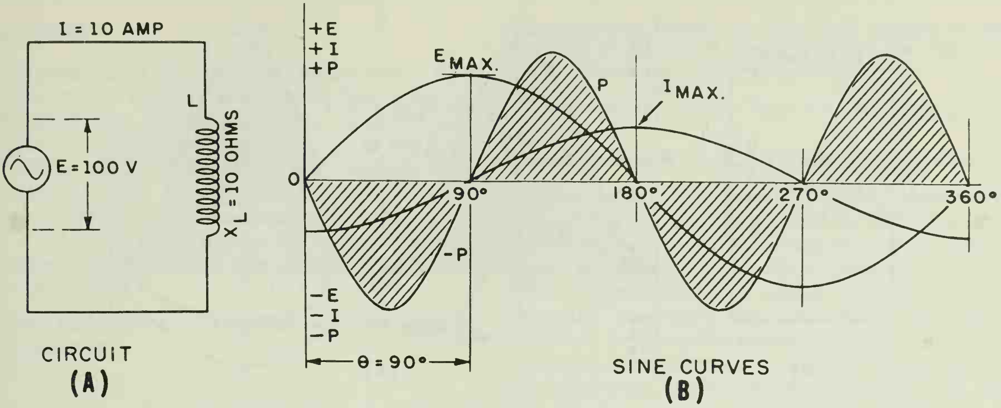


Figure 10-1.—Power in an inductive circuit.

time the current is falling, so that the average power is zero.

The product of instantaneous values of current and voltage yield the double frequency power curve *P*. (See fig. 10-1 (B).) The shaded areas under this curve above the *X* axis represent positive energy and the shaded areas below the *X* axis represent negative energy.

From 0 degrees to 90 degrees current is negative and falling; the magnetic field is collapsing and the energy in the field is being returned to the source (negative energy). The product of negative current and positive voltage is negative power.

From 90 degrees to 180 degrees the current is positive and rising; energy from the source is being stored in the rising magnetic field (positive energy). The product of positive current and positive voltage is equal to positive power.

From 180 degrees to 270 degrees current is positive and falling. Again energy is being returned to the source; the product of positive current and negative voltage is negative power.

From 270 degrees to 360 degrees current is negative and rising. Energy (positive) is being supplied by the source and stored in the magnetic field. The product of negative current and negative voltage is positive power.

Thus when current is rising, power is being supplied by the source and stored in the magnetic field; when current is falling, power is being returned to the source from the collapsing magnetic field. In the theoretically pure inductance shown in figure 10-1 the supplied power is equal to the returned power. Thus, average power used (true power) is zero.

The ratio of the true power to the apparent power in an a-c circuit is called the POWER FACTOR. It may be expressed as a percent or as a decimal. In the inductor of figure 10-1 (A), the power factor is $\frac{0}{1,000} = 0$. The power factor is also equal to the cos θ, where θ is the phase angle between the current and voltage. The phase angle between *E* and *I* in the inductor is $\theta = 90°$. Thus the power factor of an inductor of negligible losses is cos $90° = 0$. The apparent power in a purely inductive circuit is called REACTIVE POWER and the unit of reactive power is called the VAR. This unit is derived from the first letters of the words volt-ampere-reactive.

RESISTANCE IN AN A-C CIRCUIT

In an a-c circuit containing only resistance, the current and voltage are always in phase ($\theta = 0°$). (See fig. 10-2.) The true power dissipated in heat in a resistor in an a-c circuit when sine waveforms of voltage and current are applied is equal to the product of the r.m.s. volts and the r.m.s. amperes. In the circuit of figure 10-2 (A) the power absorbed by the resistor is $P = EI = 100 \times 10 = 1{,}000$ watts. The product of the instantaneous values of current and voltage (fig. 10-2 (B)) gives the power curve, *P*, the axis of which is displaced above

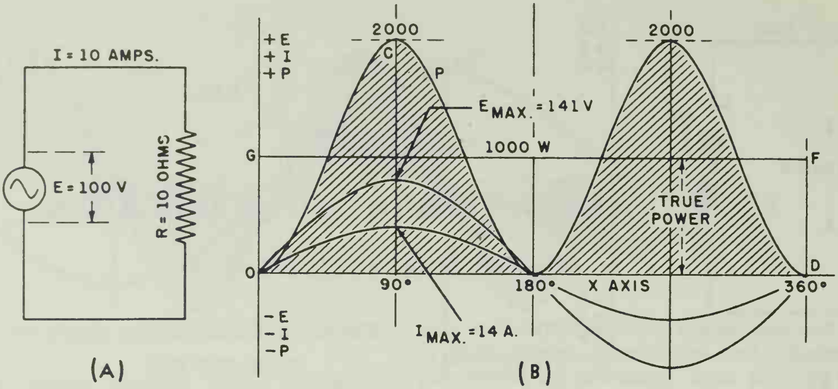


Figure 10-2.—Relation between E, I, and P in a resistive circuit.

the X axis by an amount that is proportional to 1,000 watts.

The true average power is

$$P = \frac{E_{\max} \times I_{\max}}{2} = E_{\text{eff}} \times I_{\text{eff}}.$$

The power factor of a resistive circuit is cos 0° = 1, or 100 percent. The apparent power in the resistor is also equal to the true power. The reactive power in the resistive circuit is zero.

RESISTANCE AND INDUCTIVE REACTANCE IN SERIES

Because any practical inductor must be wound with wire that has resistance, it is not possible to obtain a coil without some resistance. The resistance associated with a coil may be considered as a separate resistor, R, in the series with an inductor, L, which is purely inductive and contains only inductive reactance (fig. 10-3 (A)). The resistance has been exaggerated in this example to be of the same order of magnitude as the inductive reactance of the inductor in order to simplify the trigonometric solution.

If an alternating current, I_O, flows through the inductor a voltage drop occurs across both the resistor and the inductor. The voltage, E_r, across the resistor is in phase with the current, and the voltage drop, E_L, across the inductor leads the current by 90° (fig. 10-3 (B)). The voltage across the resistor is assumed to be 50 volts and the voltage across the inductor, 86.6 volts. These two voltages are 90° out of phase, as indicated in the figure. The applied voltage, E_O, is the hypotenuse of a right triangle, the sides of which are 50 and 86.6, respectively. Thus,

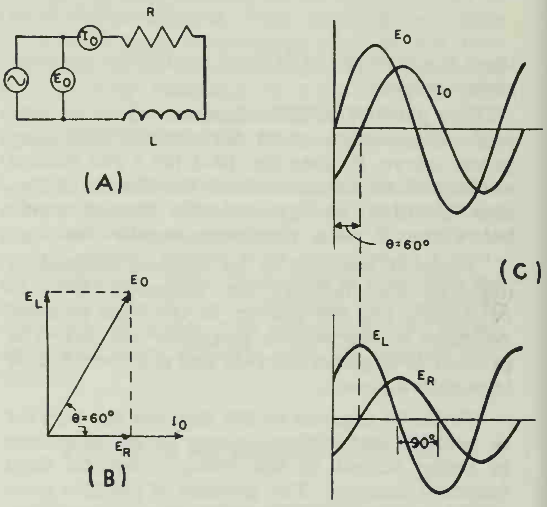


Figure 10-3.—Resistance and inductive reactance in series.

$$E_0 = \sqrt{50^2 + 86.6^2} = 100 \text{ volts.}$$

The sine curves of circuit current, I_O, applied voltage, E_O, the voltage across the coil, E_L, and the voltage across the resistor, E_r, are shown in figure 10-3 (C).

Impedance

Impedance is the total opposition to the flow of alternating current in a circuit that contains resistance and reactance. In the case of pure inductance, inductive reactance, X_L is the total opposition to the flow of current through it. In the case of pure resistance, R represents the total opposition. The combined opposition of R and X_L in series or in parallel to current flow is called IMPEDANCE. The symbol for impedance is Z.

The impedance of resistance in series with inductance is

$$Z = \sqrt{R^2 + X_L^2},$$

where Z, R, and X_L are the hypotenuse, base, and altitude respectively of a right triangle in which $\cos\theta = \frac{R}{Z}$, $\sin\theta = \frac{X_L}{Z}$, and $\tan\theta = \frac{X_L}{R}$. As mentioned before, $\cos\theta$ is equal to the circuit power factor; $\sin\theta$ is sometimes referred to as the reactive factor; and $\tan\theta$ is referred to as the quality, or Q, of a circuit or a circuit component. The trigonometric functions including the sine, cosine, and tangent of angles between 0° and 90° are given in appendix VI at the end of this training manual.

Power in a Series Circuit Containing R and X_L

The true power in any circuit is the product of the applied voltage, the circuit current, and the cosine of the phase angle between them. Thus, in figure 10-4, the true power is

$$P = EI\cos\theta = 100 \times 7.07\ (\cos 45° = 0.707) = 500 \text{ watts.}$$

The power curve is partly above the X axis (fig. 10-4 (B)) and partly below it. The axis of the power curve is displaced above the X axis an amount proportional to the true power, $EI \cos\theta$. The apparent power in this circuit is

$$100 \times 7.07 = 707 \text{ volt-amperes.}$$

The power factor is

$$\cos\theta = \frac{\text{true power}}{\text{apparent power}} = \frac{500}{707} = 0.707, \text{ or } 70.7 \text{ percent.}$$

The reactive power in the L-R circuit is the product of $EI \sin\theta$ where $\sin\theta$ is the reactive factor. Thus the reactive power is

$$100 \times 7.07\ (\sin 45° = 0.707) = 500 \text{ VARS (lagging).}$$

Summary of E, Z, and P Relations in L-R Circuit

The relation between voltage, impedance, and power in a series L-R circuit with sine waveforms applied is summarized in figure 10-5. In this example the circuit contains 12 ohms of resistance in series with 16 ohms of inductive reactance (fig. 10-5 (A)). The phase relations between the applied voltage; the voltage across the resistance, R; and the voltage across the inductance, L; are shown in figure 10-5 (B). The IR drop across R is 5 x 12 = 60 volts and forms the base of the right triangle. The altitude is the IX_L drop, or 5 x 16 = 80 volts, across L. The applied voltage represents the vector sum of the IR drop and the IX_L drop and is the hypotenuse of the right triangle. Its magnitude is 100 volts. All voltages are effective values.

The relation between resistance, inductive reactance, and impedance is shown by the vectors of figure 10-5 (C). The resistance of 12 ohms forms the base of the right triangle. The altitude of this triangle represents the inductive reactance of the coil and has a magnitude of 16 ohms. The combined impedance of the circuit is $Z = \sqrt{12^2 + 16^2} = 20$ ohms. In this triangle $\cos\theta = \frac{R}{Z}$. Thus $\cos\theta = \frac{12}{20} = 0.6$, from which $\theta = 53.1°$.

The relation between apparent power, true power, and reactive power is shown in figure 10-5 (D). The hypotenuse represents the apparent power and is equal to EI, or 100 x 5 = 500 volt-amperes. The base represents true power and is equal to $EI \cos\theta$, or 100 x 5 x 0.6 = 300 watts, where 0.6 = cos 53.1°. The altitude represents reactive power and is equal to $EI \sin\theta$, or 100 x 5 x 0.8 = 400 VARS, where 0.8 = sin 53.1°.

In all three vector diagrams the right triangles are similar. The common factor of current, I, makes their corresponding sides proportional. Thus the voltage triangle of figure 10-5 (B), is obtained by multiplying the corresponding sides of the impedance triangle of figure 10-5 (C), by I. The hypotenuse is equal to the applied voltage, or IZ = 5 x 20 = 100 volts. The base is equal to the voltage across R, or IR = 5 x 12 = 60 volts. The altitude is equal to

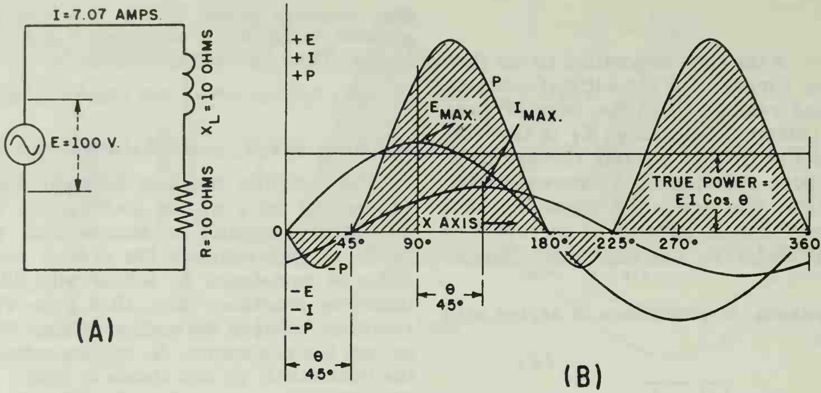


Figure 10-4.—Power in a circuit containing L and R in series.

the voltage across L, or $IX_L = 5 \times 16 = 80$ volts.

Multiplying corresponding sides of the voltage triangle by I gives the power triangle of figure 10-5 (D). The hypotenuse is IZ times I, or $I^2Z = 5^2 \times 20 = 500$ volt-amperes of apparent power. The base is IR times I, or $I^2R = 5^2 \times 12 = 300$ watts of true power. The altitude is IX_L times I, or $I^2X_L = 5^2 \times 16 = 400$ VARS of reactive power.

In the three vector diagrams, the circuit power factor is equal to the following ratios: In the voltage diagram,

$$\cos\theta = \frac{IR}{IZ} = \frac{60}{100} = 0.6.$$

In the impedance diagram,

$$\cos\theta = \frac{R}{Z} = \frac{12}{20} = 0.6.$$

In the power diagram,

$$\cos\theta = \frac{I^2R}{I^2Z} = \frac{300}{500} = 0.6.$$

In all three diagrams $\theta = 53.1°$ and the power factor is 60 percent.

Capacitive Reactance

Capacitance was defined in chapter 9 as that quality of a circuit that enables energy to be stored in an electric field. A capacitor is a device that possesses the quality of capacitance. In simple form it has been shown to consist of two parallel metal plates separated by an insulator, called a DIELECTRIC. The electric field consists of parallel lines of electric force which terminate in a positive charge on one plate and a negative charge on the other. The positive and negative charges on the plates establish the electric field in the dielectric because the dielectric prevents these charges from neutralizing each other.

CURRENT FLOW IN A CAPACITIVE CIRCUIT

A capacitor that is initially uncharged tends to draw a large current when a d-c voltage is first applied. During the charging period, the capacitor voltage rises. After the capacitor has received sufficient charge the capacitor voltage equals the applied voltage and the current flow ceases. If a sine-wave a-c voltage is applied to a pure capacitance the current is a maximum when the voltage begins to rise from zero, and the current is zero when the voltage across the capacitor is a maximum (fig. 10-6 (A)). The current leads the applied voltage by 90°, as indicated in the vector diagram of figure 10-6 (B).

ACTORS THAT CONTROL CHARGING CURRENT

Because a capacitor of large capacitance can store more energy than one of small capacitance, a larger current must flow to charge

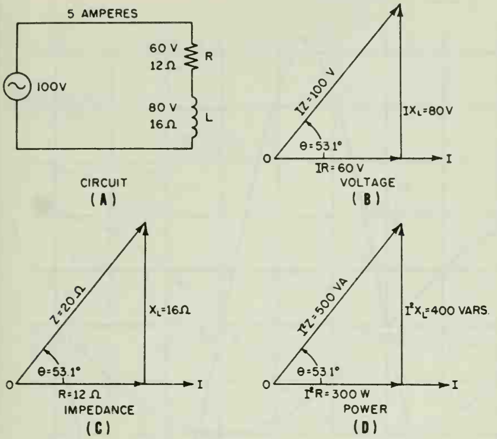


Figure 10-5.—Summary of relation between E, Z, and P in a series L-R circuit.

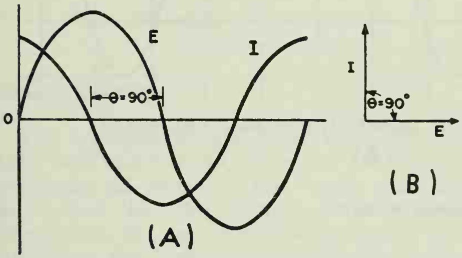


Figure 10-6.—Phase relation between E and I in a capacitive circuit.

a large capacitor than to charge a small one, assuming the same time interval in both cases. Also, because the current flow depends on the rate of charge and discharge, the higher the frequency, the greater is the current flow per unit time.

The charging current in a purely capacitive circuit varies directly with the capacitance, voltage, and frequency—

$$I = 2\pi fCE$$

where I is effective current in amperes, f is in cycles per second, C is the capacitance in farads, and E is in effective volts.

FORMULA FOR CAPACITIVE REACTANCE

The ratio of the effective voltage across the capacitor to the effective current is called the CAPACITIVE REACTANCE, X_C, and represents the opposition to current flow in a capacitive circuit of zero losses—

$$X_c = \frac{1}{2\pi fC}$$

When f is in cycles per second, and C is in farads, then X_C is in ohms.

Example: What is the capacitive reactance of a capacitor operating at a frequency of 60 cycles per second and having a capacitance of 133 microfarads, or 1.33×10^{-4} farads?

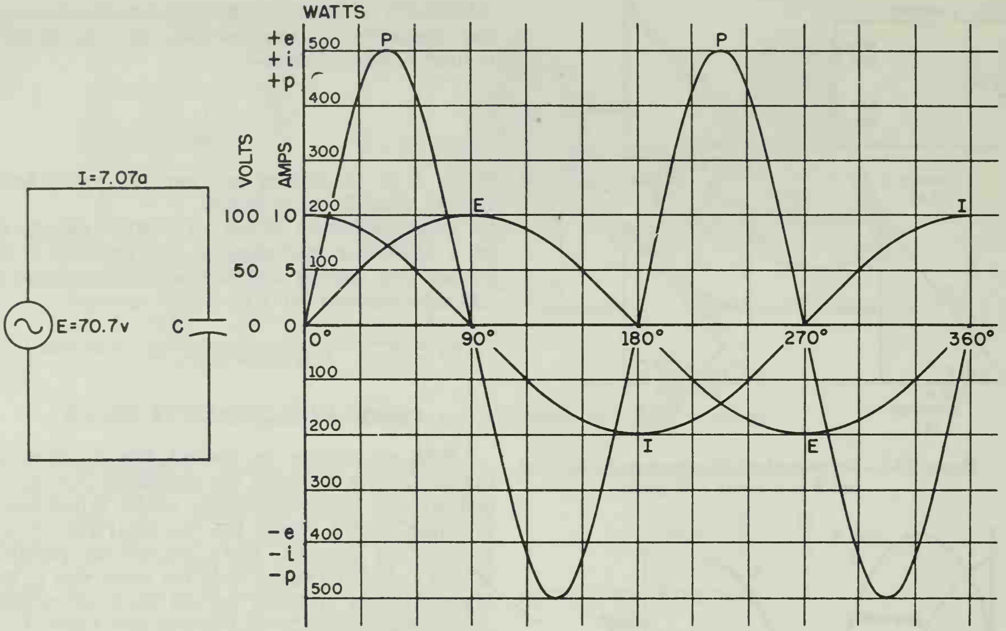
$$X_c = \frac{1}{2\pi fC} = \frac{1}{6.28 \times 60 \times 1.33 \times 10^{-4}} = 20 \text{ ohms.}$$

POWER IN A CAPACITIVE CIRCUIT

With no voltage or charge, the electrons in the dielectric between the capacitor plates rotate around their respective nuclei in normally circular orbits. When the capacitor receives a charge the positive plate repels the positive nuclei and at the same time the electrons in the dielectric are strained toward the positive plate and repelled away from the negative plate. This distorts the orbits of the electrons in the direction of the positive charge. During the time the electron orbits are changing from normal to the strained position there is a movement of electrons in the direction of the positive charge. This movement constitutes the DISPLACEMENT CURRENT in the dielectric. When the polarity of the plates reverses, the electron strain is reversed. If a sine-wave voltage is applied across the capacitor plates the electrons will oscillate back and forth in a direction parallel to the electrostatic lines of force. DISPLACEMENT CURRENT is a result of the movement of bound electrons, whereas CONDUCTION CURRENT represents the movement of free electrons.

Figure 10-7 (A) shows a capacitive circuit and figure 10-7 (B) indicates the sine waveform of charging current, applied voltage, and instantaneous power. The effective voltage is 70.7 volts. The effective current is 7.07 amperes. Because the losses are neglected, the phase angle between current and voltage is assumed to be 90°. The true power is zero, as indicated by the expression

$$\begin{aligned} P &= EI \cos \theta \\ &= 70.7 \times 7.07\ (\cos 90^\circ = 0) = 0 \text{ watt.} \end{aligned}$$



CAPACITIVE CIRCUIT

(A)

SINE CURVES OF CURRENT, VOLTAGE AND POWER

(B)

Figure 10-7.—Power in a capacitive circuit.

Multiplying instantaneous values of current and voltage over one cycle, or 360°, gives the power curve, *P*. During the first quarter cycle (from 0° to 90°) the applied voltage rises from zero to a maximum and the capacitor is receiving a charge. The power curve is positive during this period and represents energy stored in the capacitor. From 90° to 180° the applied voltage is falling from maximum to zero and the capacitor is discharging. The corresponding power curve is negative and represents energy returned to the circuit during this interval. The third quarter cycle represents a period of charging the capacitor and the fourth quarter cycle represents a discharge period. Thus, the average power absorbed by the capacitor is zero. The action is like the elasticity of a spring. Storing a charge in the capacitor is like compressing the spring. Discharging the capacitor is like releasing the pressure on the spring, thus allowing it to return the energy that was stored within it on compression.

The apparent power in the capacitor is EI = 70.7 x 7.07 = 500 volt-amperes. The reactive power in the capacitor is

$$EI \sin\theta = 70.7 \times 7.07 \times (\sin 90^\circ = 1) = 500 \text{ VARS (leading)}.$$

CAPACITIVE REACTANCE AND RESISTANCE IN SERIES

Losses that appear in capacitive circuits may be lumped in a resistor connected in series with the capacitor, as indicated in figure 10-8. In this example a 39.8-microfarad capacitor is connected in series with a 20-ohm resistor (fig. 10-8 (A)). The applied voltage across the *R-C* series circuit is 134 volts and the frequency is 100 cycles per second.

The capacitive reactance at this frequency is

$$X_c = \frac{1}{2\pi fC} = \frac{1}{6.28 \times 100 \times 39.8 \times 10^{-6}} = 40 \text{ ohms}.$$

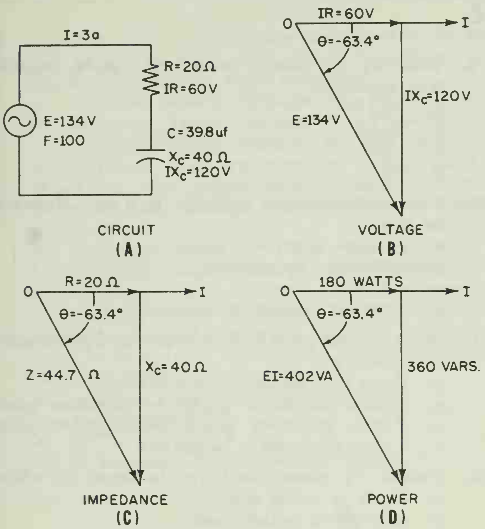


Figure 10-8.—Capacitive reactance and resistance in series.

Voltage Relation

The voltages across R and C are 90° out of phase and equal to 60 volts and 120 volts respectively, as shown in the vector diagram of figure 10-8 (B). The voltage across C is represented as IX_c and is plotted vertically downward from the horizontal in order in indicate that the current leads the voltage across the capacitor by 90°. Angle θ between the voltage across the capacitor and the circuit current is represented as -90° because it is measured clockwise from the horizontal reference vector, OI. The total voltage is equal to the vector sum of IR and IX_c and is represented in the figure as the hypotenuse of a right triangle the base of which represents the voltage across R, having an effective value of 60 volts and the voltage drop across C, having an effective value of 120 volts. The total (applied) voltage is 602 - 1202 - 134 volts.

Impedance

The total impedance, Z, of the series circuit is

$$Z = \frac{E}{I} = \frac{134}{3} = 44.7 \text{ ohms.}$$

The impedance diagram is indicated in figure 10-8 (C). The base of the triangle represents the resistance, R, of the circuit and has a magnitude of 20 ohms. The capacitive reactance, X_c is represented as the altitude of the triangle and has a magnitude of 40 ohms. The total impedance may be represented as the hypotenuse of the triangle and has a magnitude of $\sqrt{20^2 + 40^2}$ = 44.7 ohms, which is also the ratio of the applied voltage to the circuit current. The impedance diagram is a right triangle that is similar to the triangle representing the voltage relation in figure 10-8 (B).

Power

The power relations are indicated in the vector diagram of figure 10-8 (D). This diagram is also a right triangle similar to the other two. The base represents the true power absorbed by the circuit resistance and has a magnitude of $I^2R = 3^2 \times 20 = 180$ watts. The altitude represents the reactive volt-ampere (leading) and has a magnitude of $I^2X_C = 3^2 \times 40 = 360$ VARS. The total apparent power is

$$EI = 134. \times 3 = 402 \text{ volt-amperes.}$$

Summary of E, Z, and P Relations in R-C Circuits

As mentioned previously, all three triangles are similar. The common factor is the circuit current; and the phase angle, θ, between E and I is equal to the same value in all three diagrams. Thus, the circuit power factor is equal to

$$\cos \theta = \frac{IR}{IZ} = \frac{60}{134} = 0.446 \text{ (fig. 10-8, B)}$$

$$\cos \theta = \frac{R}{Z} = \frac{20}{44.7} = 0.446 \text{ (fig. 10-9, C)}$$

$$\cos \theta = \frac{I^2R}{I^2Z} = \frac{180}{402} = 0.446 \text{ (fig. 10-8, D)}$$

and angle $\theta = 63.4°$ in all three triangles.

The true power is

$$EI \cos \theta = 134 \times 3 \times (\cos 63.4° = 0.446) = 180 \text{ watts.}$$

The reactive power is

$$EI \sin \theta = 134 \times 3 \times (\sin 63.4° = 0.894) = 360 \text{ VARS.}$$

The apparent power is

$$EI = 134 \times 3 = 402 \text{ volt-amperes.}$$

QUIZ

1. When frequency is increased in an inductive circuit, the current flow will
   a. increase because of greater inductive voltage
   b. increase because of less inductive voltage
   c. decrease because of greater inductive voltage
   d. decrease because of less inductive voltage

2. The unit of measurement for reactive power is the
   a. Volt Amp (VA)
   b. Volt Amp Wattage (VAW)
   c. Volt Amp Reactive (VAR)
   d. Volt Amp Kilo Watt (KVAW)

3. The prime factors that determine inductive reactance are
   a. frequency and current
   b. frequency and induced voltage
   c. inductance and frequency
   d. inductance and voltage

4. What are the prime factors affecting capacitive reactance?
   a. Frequency and capacitance
   b. Frequency and inductance
   c. Frequency and resistance
   d. Frequency squared

5. The reaction of an inductor to any change in current is known as inductive
   a. reactance
   b. voltage
   c. current
   d. resistance

6. What two quantities comprise the total power of an a-c circuit?
   a. Apparent power and VARS
   b. True power and VARS
   c. True power and VAWS
   d. True power and power factor

7. Power factor is the
   a. percentage of apparent power expended in heat
   b. amount of apparent power in an a-c circuit
   c. amount of apparent power plus true power
   d. efficiency of a circuit expressed as an angle

8. The unit of measurement for inductive reactance is the
   a. ohm
   b. volt
   c. ampere
   d. henry

9. What is the power factor of a pure capacitive circuit?
   a. 70.7%
   b. 86.6%
   c. 100%
   d. 0%

10. The self-induced voltage in a coil depends on the
    a. voltage applied
    b. inductive reactance
    c. c.e.m.f.
    d. current change in the coil

11. What is the path for current flow through a capacitor?
    a. Does not actually flow through
    b. From negative plate to positive plate
    c. From positive plate to negative plate
    d. From dielectric to plates

12. Power is described as the rate at which
    a. work is being done
    b. energy is being used
    c. energy is being expended
    d. all of the above are correct

13. What is the power characteristic of a pure inductive circuit?
    a. Positive power is the largest
    b. Positive and negative power are equal
    c. Negative power is the largest
    d. Negative power is the smallest

14. The vector sum of X_C and R in a series R-C circuit is the total
    a. opposition to voltage in the circuit
    b. capacitive reactance in the circuit
    c. resistance in the circuit
    d. opposition to current flow in the circuit

15. Self-induced voltage in an inductor will always oppose
    a. the applied voltage by 180 degrees
    b. circuit current
    c. the applied voltage by 90 degrees
    d. the circuit current by 180 degrees

16. What is the value of apparent current flow in a capacitive circuit when it is first energized?
    a. No current flow in a capacitive circuit
    b. Minimum
    c. Maximum
    d. Zero

17. What is the phase relationship between current and voltage in a resistive circuit?
    a. 90° phase difference
    b. 0° phase difference
    c. Out of phase
    d. Cannot be determined without numerical value of R

18. Voltage and current are considered to be out of phase with each other in a pure inductive circuit by what amount?
    a. Current leads voltage by 90 degrees
    b. Current lags voltage by 90 degrees
    c. Current leads voltage by 180 degrees
    d. Current lags voltage by 180 degrees
19. What is the phase relationship between current and voltage in a pure capacitive circuit?
    a. No phase angle
    b. Current lags voltage by 90 degrees
    c. Voltage leads current by 90 degrees
    d. Voltage lags current by 90 degrees
20. The phase angle between current and voltage in a circuit containing both resistive and inductive elements is
    a. greater than 0° but less than 90°
    b. a constant 45°
    c. 90° at all times
    d. 0° because X_L and R are equal
21. In the formula for capacitive reactance, the symbol "C" represents capacitance in
    a. farads
    b. micromicrofarads
    c. microfarads
    d. ohms
22. What is the effect on capacitor voltage when frequency is increased?
    a. Voltage increases
    b. Voltage decreases
    c. Voltage not affected
    d. Voltage is minimum
23. What is impedance?
    a. Opposition to current flow in an a-c circuit created by resistance and reactances
    b. Resistance of an a-c circuit
    c. Vector sum of voltage drops in an a-c circuit
    d. Current divided by voltage in an a-c circuit

CHAPTER 11

FUNDAMENTAL ALTERNATING-CURRENT CIRCUIT THEORY

In the preceding chapter, terms were clarified, a-c reactance was explained, and the effects of individual inductors and capacitors were described. To do this, only the simplest two-element R-L and R-C series circuits were employed. In this chapter, the subject coverage will be expanded to include more complex reactive circuits.

RESISTANCE, INDUCTANCE, AND CAPACITANCE IN SERIES

Relation of Voltages and Current in an R-L-C Series Circuit

When resistive, inductive, and capacitive elements are connected in series, their INDIVIDUAL characteristics are unchanged. That is, the current through and the voltage drop across the resistor are in phase while the voltage drops across the reactive components (assuming pure reactances) and the current through them are 90 degrees out of phase. However, a new relation must be recognized with the introduction of the three-element circuit. This pertains to the effect on total line voltage and current when connecting reactive elements in series, whose individual characteristics are opposite in nature, such as inductance and capacitance. Such a circuit is shown in figure 11-1.

In the figure, note first that CURRENT is the common reference for all three element voltages, because there is only one current in a series circuit, and it is common to all elements. The common series current is represented by the dashed line in figure 11-1 (A). The voltage vector for each element, showing its individual relation to the common current, is drawn above each respective element. The total source voltage E is the vector sum of the individual voltages of IR, IX_L, and IX_C.

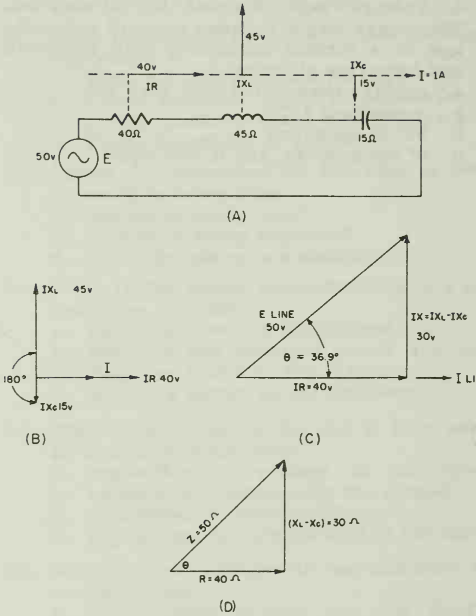


Figure 11-1.—Resistance, inductance, and capacitance connected in series.

The three element voltages are arranged for summation in part (B). Since IX_L and IX_C are each 90° away from I, they are therefore 180° from each other. Vectors in direct opposition (180° out of phase) may be subtracted directly. The total reactive voltage E_X is the difference of IX_L and IX_C. Or, $E_X = IX_L - IX_C = 45 - 15 = 30$ volts. The final relationship of line voltage and current, as seen from the source, is shown in part (C). Had X_C been larger than X_L, the voltage would lag, rather than lead. When X_C and X_L are of equal values, line voltage and current will be in phase.

Impedance of R-L-C Series Circuits

The impedance of an R-L-C (three-element) series circuit is computed in exactly the same manner described for the two-element circuits in the preceding chapter. However, there is one additional operation to be performed. That is, the DIFFERENCE of X_L and X_C must be determined prior to computing total impedance. When employing the Pythagorean Theorem-based formula for determining series impedance, the net reactance of the circuit is represented by the quantity in parenthesis $(X_L - X_C)$. Applying this formula to the circuit in figure 11-1, the impedance is

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

$$= \sqrt{40^2 + (45 - 15)^2}$$

$$= \sqrt{1{,}600 + 900}$$

$$= \sqrt{2{,}500}$$

$$Z = 50\,\Omega.$$

Series impedance may also be determined by the use of vectorial layout, or triangulation. In an impedance triangle (fig. 11-1 (D)) for a series circuit, the base always represents the series resistance, the altitude represents the NET reactance $(X_L - X_C)$, and the hypotenuse represents total impedance.

It should be noted that as the DIFFERENCE of X_L and X_C becomes greater, total impedance also increases. Conversely, when X_L and X_C are equal, their effects cancel each other, and impedance is minimum, equal only to the series resistance. When X_L and X_C are equal, their INDIVIDUAL voltages are 90° out of phase with current, but their COLLECTIVE effect is zero, because they are equal and opposite in nature. Therefore, when X_L and X_C are equal, line voltage and current are in phase. This condition is the same as if there were only resistance and no reactances in the circuit. A circuit in this condition is said to be at RESONANCE.

Power in an R-L-C Series Circuit

Total true power in an R-L-C series circuit is the product of line voltage and current, times the cosine of the angle between them. When X_L and X_C are equal, total impedance is at a minimum, and thus current is maximum. When maximum current flows, the series resistor dissipates maximum power. When X_L and X_C are made unequal, total impedance increases, line current decreases, and moves out of phase with line voltage. Both the decrease in current and the creation of a phase difference cause a decrease in true power.

INDUCTANCE AND RESISTANCE IN PARALLEL

If the voltage applied across a resistor and inductor in parallel has a sine waveform, the currents in the branches will also have sine waveforms. In the parallel circuit of figure 11-2 (A), the applied voltage, E, has a magnitude of 100 volts (r.m.s.). Branch ① contains a 20-ohm resistor, and the current, I_1, is equal to $\frac{100}{20}$, or 5 amperes (r.m.s.). This current is in phase with E. Branch ② contains an inductance of 0.053 henry. The line frequency is 60 cycles and the INDUCTIVE REACTANCE is

$$X_L = 2\pi f L = 6.28 \times 60 \times 0.053 = 20 \text{ ohms.}$$

The true power losses associated with the inductor in this example are considered negligible. Therefore, current I_2 is equal to $\frac{100}{20}$, or 5 amperes. This current lags E by an angle of 90°. (In an inductive circuit the current always lags the voltage by some angle.)

The sine waveforms of applied voltage and current are shown in figure 11-2 (B). I_1 is in phase with E. I_2 lags E by an angle of 90°. The total current, I_t, lags E by an angle of 45°.

Current Vectors

A polar-vector diagram representing the three currents and the applied voltage is shown in figure 11-2 (C). Vector OE represents the effective value of the applied voltage and is the horizontal reference vector for both branches because it is common to both branches. Vector

I_1 is the effective current of 5 amperes in branch ①. This vector is in the same line as vector OE because the current and voltage in the resistive circuit are in phase. Vector I_2 is the effective current of 5 amperes in branch ② and lags vector OE by an angle of 90°. I_1 is called the ENERGY COMPONENT of the circuit current. It flows in the resistive branch in which true power is absorbed from the source and is dissipated as heat. I_2 is called the NON-ENERGY COMPONENT of the circuit current. This current flows in the inductive branch where the true power is zero, and the reactive power is exchanged with the source twice during each cycle of applied voltage.

The total circuit current, I_t, is represented as the diagonal of the parallelogram, the sides of which are I_1 and I_2 (fig. 11-2 (C)). In this example, the sides are 5 amperes (r.m.s.) each and the diagonal is 7.07 amperes (r.m.s.).

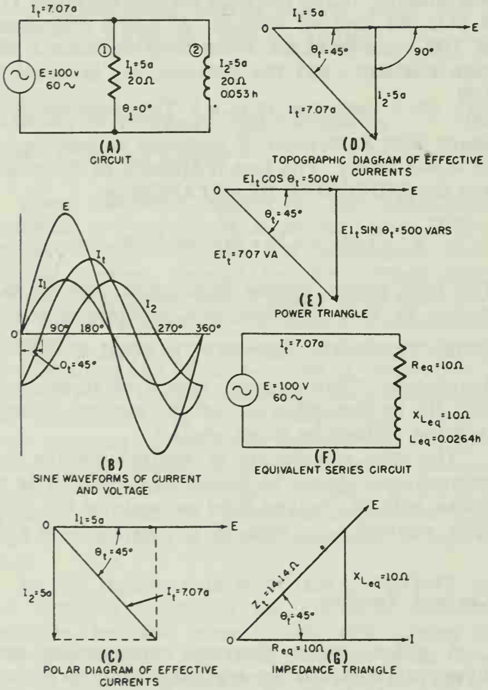

I_t=7.07a
①
②
E=100v
60 ~
I_1=5a
20Ω
θ_1=0°
I_2=5a
20Ω
0.053h
(A)
CIRCUIT
O
I_1=5a
E
θ_t=45°
90°
I_2=5a
I_t=7.07a
(D)
TOPOGRAPHIC DIAGRAM OF EFFECTIVE CURRENTS
EI_t COS θ_t=500W
O
E
θ_t=45°
EI_t SIN θ_t=500 VARS
EI_t=707 VA
(E)
POWER TRIANGLE
E
I_t
I_1
I_2
O
90°
180°
270°
360°
θ_t=45°
(B)
SINE WAVEFORMS OF CURRENT AND VOLTAGE
I_t=7.07a
R_{eq}=10Ω
E=100V
60 ~
$X_{L_{eq}}$=10Ω
L_{eq}=0.0264h
(F)
EQUIVALENT SERIES CIRCUIT
O
I_1=5a
E
θ_t=45°
I_2=5a
I_t=7.07a
(C)
POLAR DIAGRAM OF EFFECTIVE CURRENTS
E
Z_t=14.14Ω
$X_{L_{eq}}$=10Ω
θ_t=45°
O
R_{eq}=10Ω
I
(G)
IMPEDANCE TRIANGLE

Figure 11-2.—Resistance and inductance in parallel.

A topographic-vector diagram representing the three currents and the applied voltage is shown in figure 11-2 (D). As in the polar diagram, OE is the reference vector. I_1, in phase with OE, is the base of the triangle. I_2, 90° out of phase with OE, is the altitude of the triangle, and is plotted downward to indicate lag. The resultant current, I_t, is the hypotenuse of the triangle. The hypotenuse is equal to the square root of the sum of the squares of the other two sides. Thus,

$$I_t = \sqrt{I_1^2 + I_2^2} = \sqrt{5^2 + 5^2} = 7.07 \text{ amperes.}$$

The phase angle between I_t and E is the angle whose cosine is

$$\frac{I_1}{I_t} = \frac{5}{7.07} = 0.707.$$

This angle is 45°.

Power and Power Factor

The apparent power, true power, and reactive power in the parallel circuit are related as the hypotenuse, base, and altitude, respectively, of a right triangle in a similar manner to that described in the preceding chapter.

The relation between apparent power, true power, and reactive power is shown in figure 11-2 (E). The hypotenuse of the right triangle represents the apparent power and is equal to EI_t, or 100 x 7.07 = 707 volt-amperes. The base of the triangle represents the true power and is equal to $EI_t \cos \theta_t$, or 100 x 7.07 x 0.707 = 500 watts, where 0.707 = cos 45°. The altitude represents the reactive power and is equal to $EI_t \sin \theta_t$, or 100 x 7.07 x 0.707 = 500 vars, where 0.707 = sin 45°. The power triangle is similar to the current triangle and is related to it by the common factor of voltage (the voltage is the same across both branches of the parallel circuit).

Because branch ① (fig. 11-2 (A)) is purely resistive and branch ② is purely inductive, the true power of the circuit is absorbed in branch ① and the reactive power is developed in branch ②. In branch ① the true power is $EI_1 \cos \theta_1$, or 100 x 5 x 1 = 500 watts, where 1 = cos 0°. In branch ② the reactive power is $EI_2 \sin \theta_2$, or 100 x 5 x 1 = 500 vars, where 1 = sin 90°.

The true power in branch ① may also be calculated as $I_1{}^2R_1$, or 5^2 x 20 = 500 watts. The reactive power in branch ② may be calculated as $I_2{}^2X_{L2}$, or 5^2 x 20 = 500 vars. The total circuit power factor is $\cos\theta_t = \frac{\text{true power}}{\text{apparent power}} = \frac{500}{707} =$ 0.707. The power factor of branch ① is $\cos\theta_1 = \cos 0° = 1$, and the power factor of branch ② is $\cos\theta_2 = \cos 90° = 0$.

Equivalent Series-Circuit Impedance

The combined impedance of the parallel circuit is

$$Z_t = \frac{E}{I_t} = \frac{100}{7.07} = 14.14 \text{ ohms.}$$

The combined impedance is also called the impedance of the equivalent series circuit. The equivalent series circuit (fig. 11-2 (F)) contains a resistor and an inductor in series that combine to give the same impedance as the total impedance, of the given parallel circuit. Thus, the current in the equivalent series circuit is equal to the total circuit current in the parallel circuit when rated voltage and frequency are applied to the circuits.

In figure 11-2 (G), the hypotenuse, Z_t, of the impedance triangle is 14.14 ohms and the phase angle, θ_t, between total current and line voltage, is 45°. The equivalent series RESISTANCE, R_{eq}, is the base of the impedance triangle and is equal to $Z_t \cos\theta$, or 14.14 x cos 45° = 10 ohms. The equivalent series REACTANCE, X_{Leq}, is the altitude of the impedance triangle and is equal to $Z_t \sin\theta_t$, or 14.14 x sin 45° = 10 ohms.

The inductance of the equivalent series circuit is

$$L_{eq} = \frac{X_L}{2\pi f} = \frac{10}{6.28 \times 60} = 0.0264 \text{ henry.}$$

Thus, in this example, the 20-ohm resistor in branch ① shunts the 0.053-henry inductor in branch ②, and the source "sees" an equivalent resistor of 10 ohms in series with an equivalent inductor of 0.0264 henry.

Equivalent Circuit of a Low-Loss Inductor

The losses in air-core inductor occur in the wire with which the inductor is wound. If the losses are small, the resistance of the wire will be small compared with the inductive reactance developed at the operating frequency. The coil resistance acts in series with the coil reactance.

An equivalent parallel circuit for a low-loss coil can be established by substituting an equivalent coil of zero losses, but having the same inductance as the given coil for one branch and a resistor for the other branch. The resistor is of such a magnitude that the same losses will occur in this branch as occur in the given coil when rated voltage and frequency are applied.

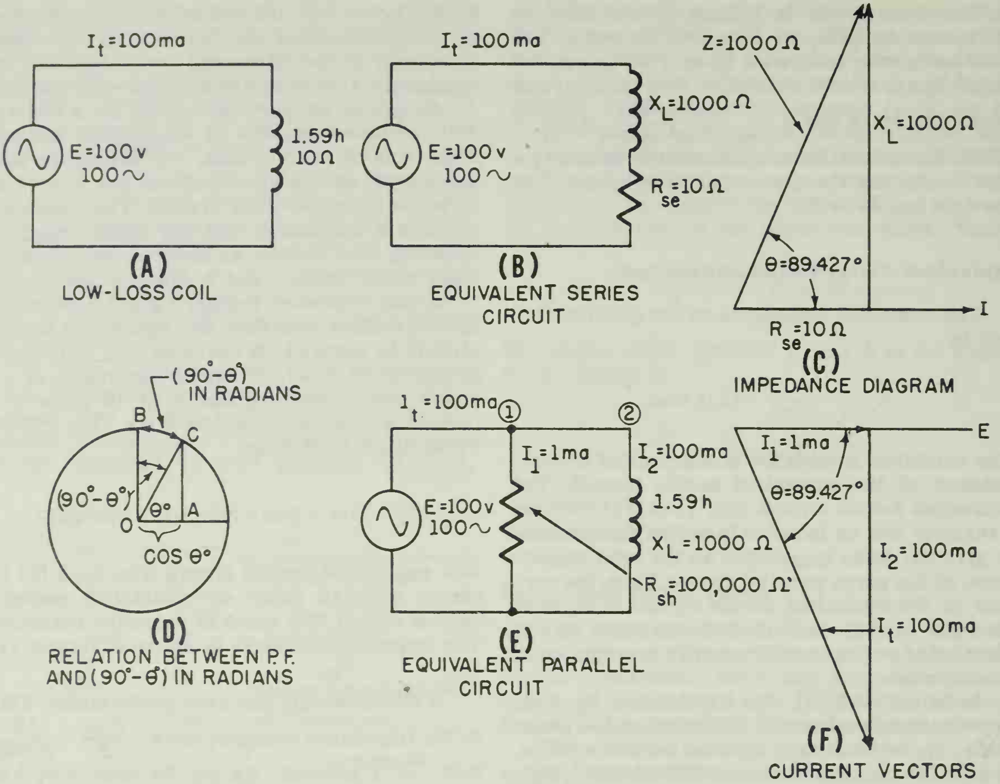
In the following example a low-loss circuit is established and then the equivalent parallel circuit is derived. A low-loss coil is indicated in figure 11-3 (A). It has an inductance of 1.59 henry and a d-c resistance of 10 ohms at an operating frequency of 100 c.p.s. The INDUCTIVE REACTANCE is

$$X_L = 2\pi f L = 6.28 \times 100 \times 1.59 = 1{,}000 \text{ ohms.}$$

The equivalent series circuit (fig. 11-3 (B)) is shown with 10 ohms of resistance acting in series with 1,000 ohms of inductive reactance. The impedance triangle is shown in figure 11-3 (C).

A low-loss coil has a low power factor. Thus, in the impedance triangle, $\cos\theta = \frac{R_{se}}{Z} = \frac{10}{1{,}000} =$ 0.01, or 1 percent. As can be seen in this example, Z is approximately equal to X_L, and $\cos\theta = \frac{R_{se}}{X_L}$. Since $\tan\theta = \frac{X_L}{R_{se}}$, it follows that in this case $\cos\theta = \frac{1}{\tan\theta}$. Thus $\tan\theta = \frac{1{,}000}{10} = 100$, and the POWER FACTOR $= \frac{10}{1{,}000}$, or 0.01, or 1 percent.

A useful relationship for finding angle θ in low-loss circuits is shown in figure 11-3 (D). This concept involves the relation between $\cos\theta$, expressed decimally, and the complementary angle, $90 - \theta$, expressed in radians. The figure indicates a unit-radius circle in which any length of arc BC measures the corresponding angle $(90 - \theta)$ which it subtends. The length of arc is equal to the angle in radians. Since 2π radians are equal to 360° it follows that 1 radian is approximately equal to $\frac{360°}{2\pi}$, or 57.3°. Thus, from a knowledge of the angle in radians, the equivalent angle θ, in degrees, is $\theta = 57.3$ x angle in radians.


I_t=100ma
E=100v
100~
1.59h
10Ω
I_t=100ma
E=100v
100~
X_L=1000Ω
R_se=10Ω
Z=1000Ω
X_L=1000Ω
θ=89.427°
I
R_se=10Ω
(90°-θ°) IN RADIANS
B
C
(90°-θ°)
θ°
O
A
COS θ°
I_t=100ma
①
②
I_1=1ma
I_2=100ma
E=100v
100~
1.59h
X_L=1000Ω
R_sh=100,000Ω
E
I_1=1ma
θ=89.427°
I_2=100ma
I_t=100ma

(A) LOW-LOSS COIL

(B) EQUIVALENT SERIES CIRCUIT

(C) IMPEDANCE DIAGRAM

(D) RELATION BETWEEN P.F. AND (90°-θ°) IN RADIANS

(E) EQUIVALENT PARALLEL CIRCUIT

(F) CURRENT VECTORS

Figure 11-3.—Equivalent circuits of a low-loss coil.

For angles greater than 84.3°, tan θ is greater than 10 and cos θ—which equals *OA*, in figure 11-3 (D)—is approximately equal to arc *BC*. Arc *BC* is a measure of the complementary angle $90 - \theta$ and is expressed in radians. Thus, cos θ is approximately equal to the angle in radians by which the current fails to be exactly 90° out of phase with the voltage. In this example, the power factor is 0.01 and therefore the angle by which the current fails to be 90° out of phase with the voltage (complementary angle) is 0.01 radian. This angle, in degrees, becomes 57.3° x 0.01, or 0.573°. Therefore, θ is equal to 90° - 0.573°, or 89.427°, and cos 89.427° = 0.01.

The relationship described in the preceding example is expressed in general terms as follows: The complementary angle, $(90 - \theta)$ in radians, is equal to the power factor, cos θ, expressed decimally, where tan θ is numerically equal to or greater than 10. From this relationship it is possible to estimate quickly the phase angle between current and voltage in low power-factor (low-loss) circuits.

The equivalent parallel circuit for the 1.59-henry coil discussed in this example is shown in figure 11-3 (E). The equivalent shunt resistor, R_{sh}, has a resistance of 100,000 ohms (to be derived later), and this resistor is connected in parallel with a 1.59-henry inductor having zero losses. With rated voltage and frequency applied, the input current to the parallel circuit has the same magnitude and phase with respect to the applied voltage as in the original coil.

The current in the resistive branch is $\frac{100}{100{,}000} = 0.001$ ampere, or 1 milliampere, and is the base of the current triangle (fig. 11-3 (F)). The current in the inductive branch is $\frac{100}{1{,}000} = 0.1$ ampere, or 100 ma., and is the altitude of the current triangle. The total current in the parallel circuit is equal to $\sqrt{1^2 + 100^2} =$ 100 milliamperes (approx.), and is the hypotenuse of the current triangle. This current lags the line voltage by an angle of 90° - (57.3° x 0.01), or 89.427°.

The equivalent series-circuit impedance triangle (fig. 11-3 (C)) is similar to the current triangle (fig. 11-3 (F)). From the impedance triangle, $\cos\theta \approx \frac{R_{se}}{X_L}$; and from the current triangle, $\cos\theta \approx \frac{I_1}{I_2}$, where I_1 is the energy current and I_2 is the nonenergy current. Therefore,

$$\frac{I_1}{I_2} = \frac{R_{se}}{X_L}. \qquad (11\text{-}1)$$

For the resistive branch,

$$I_1 = \frac{E}{R_{sh}}, \qquad (11\text{-}2)$$

and for the inductive branch,

$$I_2 = \frac{E}{X_L}. \qquad (11\text{-}3)$$

Substituting equations 11-2 and 11-3 in equation 11-1,

$$\frac{\frac{E}{R_{sh}}}{\frac{E}{X_L}} = \frac{R_{se}}{X_L}. \qquad (11\text{-}4)$$

Canceling E and transposing equation 11-4,

$$R_{sh} = \frac{X_L^2}{R_{se}}. \qquad (11\text{-}5)$$

In the example of figure 11-3, $R_{se} = 10$ ohms, $X_L = 1{,}000$ ohms, and $R_{sh} = \frac{(1{,}000)^2}{10} = 100{,}000$ ohms.

The preceding relations are sufficiently accurate for low-loss inductive circuits in which θ is 84.3° or higher, and $\tan\theta$ is 10 or higher.

Combining Currents at Acute Angles

Figure 11-4 (A) represents a 2-branch parallel circuit in which branch ① has a power factor of 0.50 and branch ② has a power factor of 0.866. The current in branch ① lags the applied voltage by an angle of 60° and the current in branch ② lags the applied voltage by an angle of 30°. The series resistance, R_1, of branch ① is 10 ohms, the series inductive reactance, X_{L1}, is 17.32 ohms, and the impedance, Z_1, is $\sqrt{10^2 + (17.32)^2} =$ 20 ohms. The series resistance, R_2, of branch ② is 17.32 ohms, the series inductive reactance, X_{L2}, is 10 ohms, and the impedance, Z_2, is $\sqrt{(17.32)^2 + 10^2} = 20$ ohms.

A topographic-vector diagram of the currents in the two branches and the total circuit current is shown in figure 11-4 (B). The current in branch ① is $I_1 = \frac{100}{20} = 5$ amperes and is the hypotenuse of the right triangle of which the base (energy component) is 5 cos 60° = 2.5 amperes and the altitude (nonenergy component) is 5 sin 60° = 4.33 amperes. The current in branch ② is $I_2 = \frac{100}{20} = 5$ amperes and is the hypotenuse of the right angle of which the base (energy component) is 5 cos 30° = 4.33 amperes and the altitude (nonenergy component) is 5 sin 30° = 2.5 amperes. The total circuit current is the vector sum of I_1 and I_2, and is the hypotenuse of the resultant right triangle, the base of which is the sum of the energy components of both branches, 2.5 + 4.33 = 6.83 amperes, and the altitude of which is the sum of the nonenergy components of both branches, 4.33 + 2.5 = 6.83 amperes. Thus,

$$I_t = \sqrt{(2.5 + 4.33)^2 + (4.33 + 2.5)^2} = 9.66 \text{ amperes.}$$

The circuit power factor is $\cos\theta_t = \frac{2.5+4.33}{9.66} =$ 0.707, and $\theta_t = 45°$.

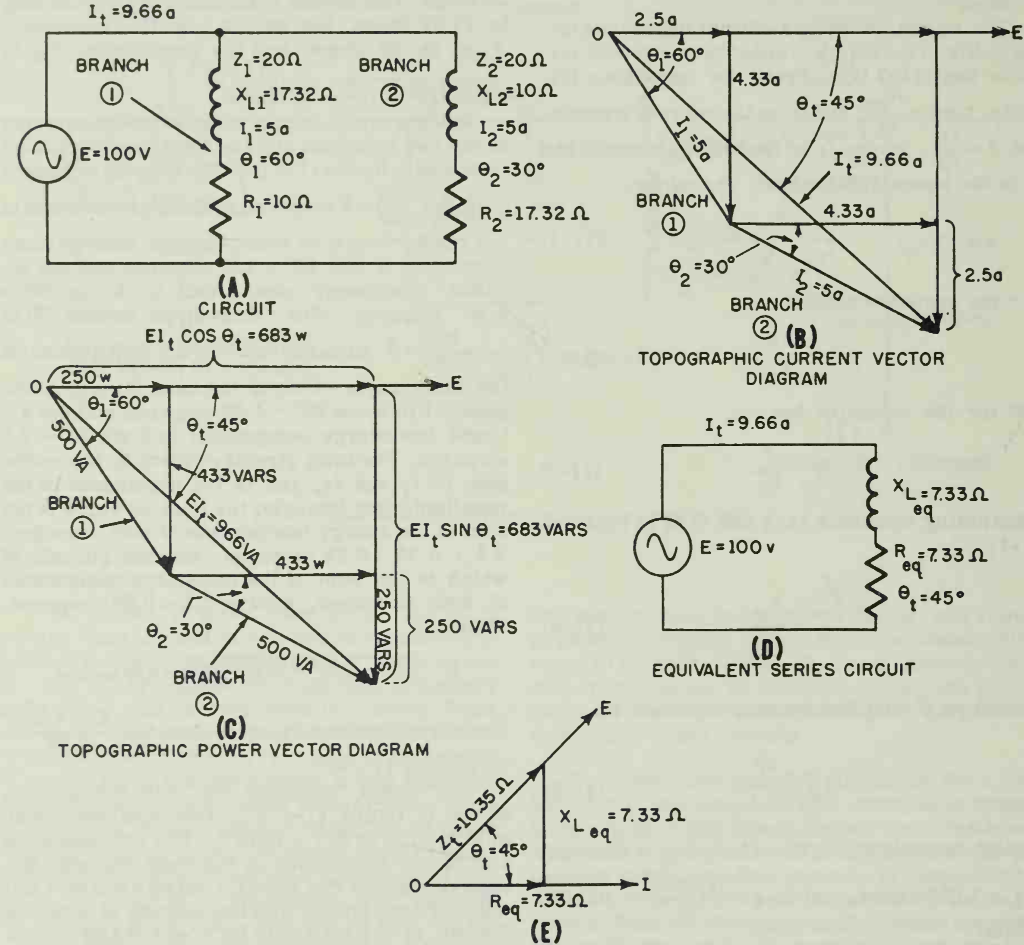
The power relations for this circuit are shown in figure 11-4 (C). The apparent power in branch ① is $EI_1 = 100 \times 5 = 500$ volt-amperes and is the hypotenuse of the right triangle, the base of which is $EI_1 \cos\theta_1 = 100 \times 5 \times \cos 60° = 250$ watts of true power, and the altitude of which is $EI_1 \sin\theta_1 = 100 \times 5 \times \sin 60° = 433$ VARS of reactive power.

The apparent power in branch ② is $EI_2 = 100 \times 5 = 500$ volt-amperes and is the hypotenuse of the right triangle, the base of which is EI_2 cos $\theta_2 = 100 \times 5 \times \cos 30° = 433$ watts of true power, and the altitude of which is EI_2 sin $\theta_2 = 100 \times 5 \times \sin 30° = 250$ VARS of reactive power.

The total apparent power of the combined parallel circuit is the hypotenuse of the resultant triangle, the base of which is equal to the sum of the true power components in both branches, and the altitude of which is equal to the sum of the reactive power components in both branches. Thus, the total apparent power $= \sqrt{(250+433)^2 + (433+250)^2} = 966$ volt-amperes.

The equivalent series circuit (fig. 11-4 (D)), representing the combined impedance of the given parallel circuit, has a total impedance, Z_t, that is determined by dividing the applied voltage, E, by the total circuit current, I_t.

$$Z_t = \frac{E}{I_t} = \frac{100}{9.66} = 10.35 \text{ ohms.}$$


I_t = 9.66 a
BRANCH ①
Z_1 = 20 Ω
X_{L1} = 17.32 Ω
I_1 = 5 a
θ_1 = 60°
R_1 = 10 Ω
BRANCH ②
Z_2 = 20 Ω
X_{L2} = 10 Ω
I_2 = 5 a
θ_2 = 30°
R_2 = 17.32 Ω
E = 100 V
2.5 a
O
E
θ_1 = 60°
4.33 a
θ_t = 45°
I_1 = 5 a
I_t = 9.66 a
BRANCH ①
4.33 a
θ_2 = 30°
I_2 = 5 a
2.5 a
BRANCH ②
EI_t COS θ_t = 683 w
250 w
θ_1 = 60°
θ_t = 45°
500 VA
433 VARS
BRANCH ①
EI_t = 966 VA
EI_t SIN θ_t = 683 VARS
433 w
250 VARS
250 VARS
θ_2 = 30°
500 VA
BRANCH ②
I_t = 9.66 a
$X_{L_{eq}}$ = 7.33 Ω
E = 100 v
R_{eq} = 7.33 Ω
θ_t = 45°
Z_t = 10.35 Ω
θ_t = 45°
$X_{L_{eq}}$ = 7.33 Ω
R_{eq} = 7.33 Ω
I

(A) CIRCUIT

(B) TOPOGRAPHIC CURRENT VECTOR DIAGRAM

(C) TOPOGRAPHIC POWER VECTOR DIAGRAM

(D) EQUIVALENT SERIES CIRCUIT

(E) EQUIVALENT SERIES IMPEDANCE DIAGRAM

Figure 11-4.—Two-branch L-R circuit with currents 30° out of phase.

The hypotenuse of the impedance triangle (fig. 11-4 (E)) is 10.35 ohms. The impedance triangle is similar to the resultant-current right triangle (fig. 11-4 (B)), and angle θ_t has the same magnitude in both triangles. This angle is equal to 45°, as determined in the current-triangle calculations.

The equivalent series resistance, R_{eq}, is the base of the impedance triangle and is equal to $Z_t \cos \theta_t$, or $10.35 \times \cos 45° = 7.33$ ohms.

The equivalent series reactance, $X_{L_{eq}}$, is the altitude of the impedance triangle and is equal to $Z_t \sin \theta_t$ or $10.35 \times \sin 45° = 7.33$ ohms.

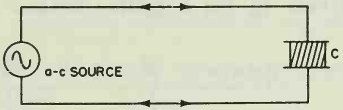
The impedance triangle is also similar to the resultant power triangle for the combined parallel circuit (fig. 11-4 (C)). The common factor between the two triangles is the square of the total circuit current, I_t^2. The base of the resultant power triangle is $I_t^2 R_{eq} = (9.66)^2 \times 7.33 =$ 683 watts of true power. This product may be checked by adding the true power components in branches ① and ②. Thus, 250 + 433 = 683 watts of true power.

The altitude of the resultant power triangle is $I_t^2 X_{L_{eq}} = (9.66)^2 \times 7.33 = 683$ VARS of reactive power. This product may be checked by adding the reactive VAR components in branches ① and ②. Thus, 433 + 250 = 683 VARS of reactive power.

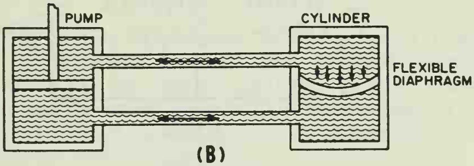
The hypotenuse of the resultant power triangle is $I_t^2 Z_t = (9.66)^2 \times 10.35 = 966$ volt-amperes of apparent power. This product may be checked by adding vectorially the apparent power in branch ① and the apparent power in branch ② This product is equal to the hypotenuse of the resultant power triangle (fig. 11-4 (C)). This product CANNOT be checked accurately by adding arithmetically the apparent power in branch ① to the apparent power in branch ② because these quantities are not in phase with each other.

CAPACITANCE AND RESISTANCE IN PARALLEL

The action of a capacitor in an a-c series circuit was described in chapter 10 and is amplified further at this time as an introduction to the a-c parallel R-C circuit. In figure 11-5 (A), an a-c voltage of sine waveform is applied across a capacitor and a charging current of sine waveform flows around the circuit in a manner something like that of the flow of water in the hydraulic analogy shown in figure 11-5 (B). The pump at the left corresponds to the a-c source and the cylinder at the right corresponds to the capacitor. If the pump piston is driven by means of a crank turning at uniform speed, the resulting motion of the water will be sinusoidal. The motion of the water is transmitted through the flexible diaphragm in the cylinder and the resulting motion, first in one direction and then in the other, corresponds to the electron flow in the wires connecting the capacitor to the a-c source.



(A)
a-c CIRCUIT



(B)
WATER ANALOGY

Figure 11-5.—Water analogy of a capacitor in an a-c circuit.

The mechanical stress in the diaphragm in the cylinder corresponds to the electric stress in the dielectric between the plates of the capacitor. Electron flow does not occur through the dielectric in the same way that water would flow through the flexible diaphragm if a hole were punctured in it. Instead, the electrons flow around the capacitor circuit on one alternation causing a negative charge to build up on one plate, and a corresponding positive charge on the other, and on the next alternation causing a reversal of the polarity of the charges on the plates. Thus, the effective impedance which the capacitor offers to the flow of ALTERNATING CURRENT can be relatively low at the same time that the insulation resistance which the dielectric offers to the flow of DIRECT CURRENT is extremely high.

In the example of figure 11-6, a 2-branch circuit consists of a 100-ohm resistor and a 15.9-microfarad capacitor of negligible losses in parallel with a 100-volt a-c source. The frequency of the source voltage is 100 c.p.s. and the voltage is assumed to have a sine waveform. The current in branch ① is $\frac{100}{100} = 1$ ampere (r.m.s) The impedance of branch ② is composed of capacitive reactance; its resistance component is neglected. In branch ② $X_C = \frac{1}{2\pi fC} = \frac{1}{6.28 \times 100 \times 15.9 \times 10^{-6}} = 100$ ohms. The current in branch ② is $\frac{100}{100} = 1$ ampere (r.m.s.). The sine waveform of the branch currents and the applied voltage, together with the resultant line current, are shown in figure 13-6 (B).

The current in the resistive branch is in phase with the applied voltage and has a peak value of $\frac{1}{0.707} = 1.41$ amperes. The current in the capacitor branch leads the applied voltage by an angle of 90° and has a peak value of $\frac{1}{0.707} =$ 1.41 amperes. The resultant line current is the algebraic sum of the instantaneous values of the currents in the two branches and has a peak value of 2 amperes. The resultant line current, I_t, leads the applied voltage by an angle of 45°.

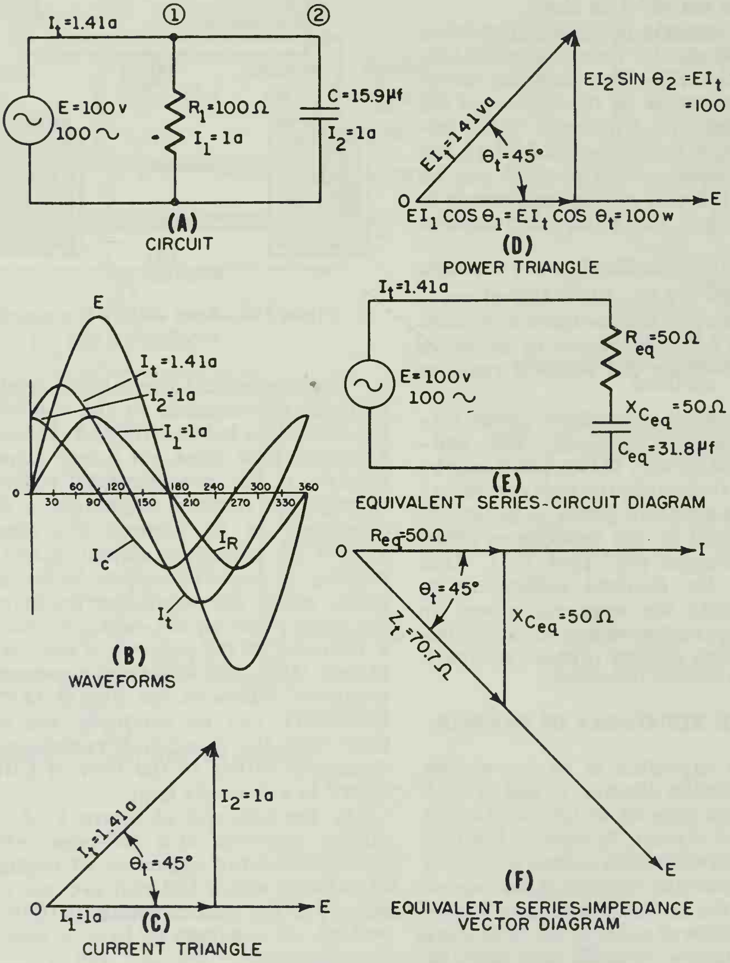

I_t=1.41a
①
②
E=100v
100 ~
R_1=100Ω
I_1=1a
C=15.9μf
I_2=1a
(A)
CIRCUIT
EI_2 SIN θ_2 =EI_t SIN θ_t
=100 VARS
EI_t=141va
θ_t=45°
O
E
EI_1 COS θ_1= EI_t COS θ_t=100w
(D)
POWER TRIANGLE
E
I_t=1.41a
I_2=1a
I_1=1a
0
30 60 90 120 150 180 210 240 270 300 330 360
I_c
I_R
I_t
(B)
WAVEFORMS
I_t=1.41a
E=100v
100 ~
R_eq=50Ω
X_Ceq=50Ω
C_eq=31.8μf
(E)
EQUIVALENT SERIES-CIRCUIT DIAGRAM
O
R_eq=50Ω
I
θ_t=45°
Z_t=70.7Ω
X_Ceq=50Ω
E
(F)
EQUIVALENT SERIES-IMPEDANCE VECTOR DIAGRAM
I_t=1.41a
I_2=1a
θ_t=45°
O
I_1=1a
E
(C)
CURRENT TRIANGLE

Figure 11-6.—Parallel R-C circuit analysis.

Current Vectors

A topographic-vector diagram of the EFFECTIVE VALUES of these currents is shown in figure 11-6 (C). The base of the current triangle is 1 ampere and represents the current in branch ①. This current is in phase with the applied voltage and represents the energy component of the total line current.

The altitude of the current triangle is 1 ampere and represents the current in branch ②. This current leads the applied voltage by 90° and represents the nonenergy component of the total line current.

The hypotenuse of the triangle is 1.41 amperes and represents the total line current.

The reference vector, *OE*, for the current triangle is the line voltage, and in the *R-C* parallel circuit, the altitude extends above the reference vector to indicate the sense of lead. This direction is opposite to that of the altitude of the current triangle for the *R-L* parallel circuit in figure 11-2 (D). In both figures the vectors are assumed to rotate in a counterclockwise direction to indicate the sense of lead or lag of the currents with respect to the line voltage. In all single-phase circuits such as these, the current vectors are considered in their relative phase by angles that never exceed 90° with respect to their common reference voltage vector.

In figure 11-2 (D), the line current lags the line voltage by an angle of 45°, and in figure 11-6 (C), the line current leads the line voltage by an angle of 45°. If both inductance and capacitance exist in the same parallel circuit as separate branches, the currents in these branches will be 180° out of phase with each other, but the current in the inductive branch will never lag the line voltage by an angle in excess of 90°, and the current in the capacitive branch will never lead the line voltage by an angle in excess of 90°

Power and Power Factor

The power triangle for the parallel *R-C* circuit is shown in figure 11-6 (D). The TRUE power in branch ① is

$$EI_1 \cos \theta_1 = 100 \times 1 \times (\cos 0^\circ = 1) = 100 \text{ watts},$$

and forms the base of the triangle in line with the voltage vector, *OE*. The REACTIVE power in branch ② is

$$EI_2 \sin \theta_2 = 100 \times 1 \ (\sin 90^\circ = 1) = 100 \text{ VARS},$$

and is the altitude of the power triangle, perpendicular to *OE*. The REACTIVE power in branch ① is

$$EI_1 \sin \theta_1 = 100 \times 1 \ (\sin 0^\circ = 0) = 0 \text{ VAR},$$

and the TRUE power in branch ② is

$$EI_2 \cos \theta_2 = 100 \times 1 \ (\cos 90^\circ = 0) = 0 \text{ watt}.$$

The APPARENT power of the parallel *R-C* circuit is

$$EI_t = 100 \times 1.41 = 141 \text{ volt-amperes}$$

and is the hypotenuse of the power triangle.

The power triangle (fig. 11-6 (D)) is similar to the current triangle (fig. 11-6 (C)), since θ_t has the same magnitude in both triangles. The total circuit power factor, as determined from the current triangle, is

$$\cos \theta_t = \frac{I_1}{I_t} = \frac{1}{1.41} = 0.707.$$

The total circuit power factor, as determined from the power triangle, is

$$\cos \theta_t = \frac{\text{true power}}{\text{apparent power}} = \frac{100}{141} = 0.707.$$

The TRUE power of the total circuit, as determined from the power triangle, is

$$EI_t \cos \theta_t = 100 \times 1.41 \ (\cos 45^\circ = 0.707) = 100 \text{ watts}.$$

This value is equal to the true power in branch ①.

The REACTIVE power of the total circuit, as determined from the power triangle, is

$$EI_t \sin \theta_t = 100 \times 1.41 \ (\sin 45^\circ = 0.707) = 100 \text{ VARS}.$$

This value is equal to the reactive power in branch ②.

Equivalent Series Impedance

The total impedance of the parallel *R-C* circuit is

$$Z_t = \frac{E}{I_t} = \frac{100}{1.41} = 70.7 \text{ ohms}.$$

As mentioned previously, the total impedance is also the impedance of the equivalent series circuit (fig. 11-6 (E)). In figure 11-6 (F), the hypotenuse, Z_t, of the impedance triangle is 70.7 ohms and the phase angle, θ_t, between total current and line voltage is 45°. The equivalent series resistance, R_{eq}, is the base of the impedance triangle and has a magnitude of

$$R_{eq} = Z_t \cos \theta_t = 70.7 \ (\cos 45^{\circ} = 0.707) = 50 \text{ ohms.}$$

The equivalent series reactance, $X_{C_{eq}}$, is the altitude of the impedance triangle and has a magnitude of $Z_t \sin \theta_t = 70.7$ ($\sin 45^{\circ} = 0.707$) = 50 ohms. The altitude is extended downward, in contrast to the upward direction of the altitude of the current triangle in figure 11-6 (C), to maintain the sense of current lead for counterclockwise vector rotation. The line voltage is the horizontal reference vector, *OE* (fig. 11-6 (C)), and the line current is the horizontal reference vector, *OI* (fig. 11-6 (F)).

The capacitance in microfarads of the equivalent series impedance is

$$C_{eq} = \frac{10^6}{2\pi f X_{C_{eq}}} = \frac{10^6}{6.28 \times 100 \times 50} = 31.8 \text{ microfarads.}$$

Thus, in this example, the 100-ohm resistor in branch ① shunts the 15.9-microfarad capacitor in branch ② and the source "sees" an equivalent resistor of 50 ohms in series with an equivalent capacitor of 31.8 microfarads (fig. 11-6 (E)).

Equivalent Circuit of a Low-Loss Capacitor

The action of a capacitor in an a-c circuit was described as being like the flow of water in a cylinder having a flexible diaphragm. The diaphragm corresponds to the dielectric in a capacitor and the mechanical stresses in the diaphragm correspond to the electric stress in the dielectric.

Most of the heating produced in a capacitor is due to the loss in the dielectric. The movement of the electrons in the atoms of a solid dielectric is pictured in figure 11-7. The capacitor is connected to a source of a-c voltage of sine waveform and the conditions are indicated for three successive instants in the cycle of applied a-c voltage.

In figure 11-7 (A), the voltage across the capacitor plates is positive maximum and the capacitor is charged. The atoms in the dielectric are subjected to electric stress that causes their orbital electrons to move in paths that are changed from circular to elliptical patterns. The elliptical pattern forms as a result of the attractive force of the negatively charged plate on the positive nucleus and the simultaneous repulsion of the positively charged plate on the nucleus. At the same time the positive plate attracts the orbital electrons, the negative plate repels them.

In figure 11-7 (B), the charge on the plates is zero and the electric stress is removed from the dielectric. In this case the orbital electrons travel in circular paths about the nucleus with no external forces applied to them.

In figure 11-7 (C), the charges on the plates are reversed and the orbital electrons are again caused to move in elliptical paths. In this case the protons (entire nucleus) are moved toward the upper plate, the forces being opposite to those developed in figure 11-7 (A).

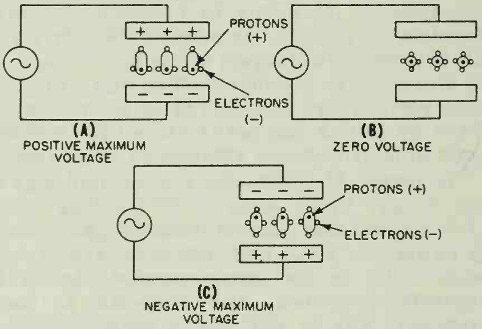
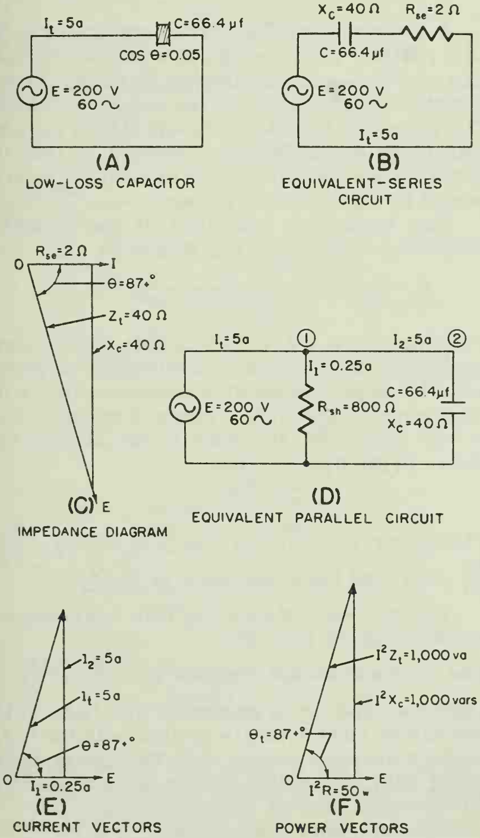


Figure 11-7.—Capacitor dielectric losses.

The rapid reversals of applied voltage accompanied by the change of the orbital electron paths from circular to elliptical and back to circular patterns cause heat to be developed in the dielectric. The change in pattern of the electron orbits constitutes a dielectric displacement current. This current is considered to be made up of two components, one leading the voltage by 90°, the other an energy component in phase with the applied voltage. Factors that determine the dielectric loss are the applied voltage, the dielectric constant, the capacitor power factor, and the frequency of the applied voltage. An air-dielectric capacitor has no appreciable loss, and the power factor is 0. A mica capacitor, having a dielectric constant of 7 and a power factor of 0.0001, has relatively low loss and low dielectric heating at high voltages and high frequencies.

The product of the dielectric constant and the power factor is called the LOSS FACTOR. The loss factor is low for good dielectrics that operate without much dielectric heating. The loss factor is the best indication of the ability of a material to withstand high voltages at high frequencies. The loss factor for the previously mentioned mica capacitor is 7 x 0.0001 = 0.0007. The loss factor for air dielectric is zero because the power factor is zero.



(A) LOW-LOSS CAPACITOR

(B) EQUIVALENT-SERIES CIRCUIT

(C) IMPEDANCE DIAGRAM

(D) EQUIVALENT PARALLEL CIRCUIT

(E) CURRENT VECTORS

(F) POWER VECTORS

Figure 11-8.—Equivalent circuits of a low-loss capacitor.

The equivalent circuits of a low power-factor capacitor are represented in figure 11-8. The circuits are derived by assuming a capacitor of the same capacitance as that of the original capacitor, but having no losses (zero power factor), to be connected (1) in SERIES with a resistor that develops the same true power loss as in the original capacitor; and (2) a capacitor of the same capacitance as that of the original capacitor, but having no losses (zero power factor), to be connected in SHUNT with a resistor that develops the same true power loss as in the original capacitor. The capacitance of the capacitor in this example is 66.4 microfarads. The power factor of the capacitor is cos θ = 0.05. The effective voltage is 200 volts and the capacitor current is 5 amperes.

The equivalent series circuit is shown in figure 11-8 (B). At the operating frequency of 60 cycles per second the capacitive reactance of the capacitor is

$$X_C = \frac{1}{2\pi f C} = \frac{1}{6.28 \times 60 \times 66.4 \times 10^{-6}} = 40 \text{ ohms approximately.}$$

The impedance of the series circuit is

$$Z_t = \frac{E}{I_t} = \frac{200}{5} = 40 \text{ ohms.}$$

The equivalent series resistance is

$$R_{se} = Z_t \cos \theta_t = 40 \times 0.05 = 2 \text{ ohms,}$$

(fig. 11-8 (B)). The base of the impedance triangle is 2 ohms of resistance (fig. 11-8 (C)), the altitude of the impedance triangle is 40 ohms of capacitive reactance, and the hypotenuse is approximately 40 ohms of impedance.

The power factor of this circuit is cos $\theta_t = \frac{R_{se}}{Z_t} = \frac{2}{40} = 0.05$, or 5 percent. In this example, as in the low-loss inductor of figure 11-3, Z_t is approximately equal to X_C, and cos $\theta_t = \frac{R_{se}}{X_C}$. Since tan $\theta_t = \frac{X_C}{R_{se}} = \frac{40}{2} = 20$, it follows that cos $\theta_t = \frac{1}{\tan \theta}$, and the power factor of the capacitor is $\frac{2}{40}$, or 0.05.

The angle whose cosine is 0.05 may be closely approximated by the previously described relation between the power factor and the complementary angle in radians. In this example, the complementary angle by which the current fails to be 90° out of phase with the voltage is 0.05 radian, or 0.05 x 57.3 = 2.865°, and $\theta = 90° - 2.865° = 87.135°$. This angle is indicated in all of the vector diagrams of figure 11-8 as 87+°

The equivalent parallel circuit for the 66.4-microfarad capacitor discussed in this example is shown in figure 11-8 (D). The equivalent series resistance and the equivalent shunt resistance are related in the equivalent capacitor circuits in the same way that R_{se} and R_{sh} are related in the low-loss inductor circuits of figure 11-3. This relation was stated in equation 11-5. Thus, in the capacitor circuits,

$$R_{sh} = \frac{(X_C)^2}{R_{se}} = \frac{(40)^2}{2} = 800 \text{ ohms.}$$

The equivalent shunt resistance of 800 ohms is connected in parallel with a 66.4-microfarad capacitor of zero losses. With rated voltage and frequency applied, the input current to the parallel circuit will have the same magnitude and phase with respect to the applied voltage as in the original capacitor.

The energy current in the resistive branch is $I_1 = \frac{E}{R_{sh}} = \frac{200}{800} = 0.25$ ampere and is the base of the current triangle (fig. 11-8 (E)). The non-energy current in the capacitive branch is $I_2 = \frac{E}{X_C} = \frac{200}{40} = 5$ amperes and is the altitude of the current triangle. The total current in the parallel circuit is equal to $\sqrt{(0.25)^2 + (5)^2} = 5$ amperes (approx.) and is the hypotenuse of the current triangle. This current leads the voltage by an angle of 87.135°.

The power relations are shown in figure 11-8 (F). The true power of the circuit may be found in a number of ways. Three methods are listed as follows:

1. $P = EI_t \cos \theta_t = 200 \times 5 \times 0.05 = 50$ watts (fig. 11-8 (A)).
2. $P = I_t{}^2R_{se} = 5^2 \times 2 = 50$ watts (fig. 11-8 (B)).
3. $P = I_1{}^2R_{sh} = (0.25)^2 \times 800 = 50$ watts (fig. 11-8 (D)).

The true power of 50 watts is the base of the power triangle (fig. 11-8 (F)).

The reactive power may be calculated in a number of ways. Three methods are indicated as follows:

1. VARS $= E_tI_t \sin \theta_t = 200 \times 5 \times (\sin 87+° = 1 \text{ approx.}) = 1{,}000$ VARS (fig. 11-8 (A)).
2. VARS $= I_t{}^2X_C = 5^2 \times 40 = 1{,}000$ VARS (fig. 11-8 (B)).
3. VARS $= I_2{}^2X_C = 5^2 \times 40 = 1{,}000$ VARS (fig. 11-8 (D)).

The reactive power of 1,000 VARS is the altitude of the power triangle (fig. 11-8 (F)).

The apparent power of the capacitor may be calculated as:

1. Apparent power $= EI_t = 200 \times 5 = 1{,}000$ VA (fig. 11-8 (A)).
2. Apparent power $= I_t{}^2Z_t = 5^2 \times 40 = 1{,}000$ VA (fig. 11-7 (B)).

The apparent power of 1,000 volt-amperes is the hypotenuse of the power triangle (fig. 11-8 (F)).

Combining Currents at Acute Angles

A 2-branch parallel circuit containing a 75-ohm resistor in branch ① and a series combination of a 79.6-microfarad capacitor and a 30-ohm resistor in branch ② is shown in figure 11-9 (A). The capacitor losses are assumed to be included with those of the 30-ohm resistor so that the power factor of that portion of branch ② represented by the capacitor is zero.

The capacitive reactance at the operating frequency of 50 cycles per second is

$$X_C = \frac{1}{2\pi fC} = \frac{1}{6.28 \times 50 \times 79.6 \times 10^{-6}} = 40 \text{ ohms.}$$

The impedance, Z_2, of branch ② is the combined opposition of 30 ohms of resistance in series with 40 ohms of capacitive reactance and is the hypotenuse of the right triangle of which 30 ohms is the base and 40 ohms is the altitude (not shown in the figure). Thus,

$$Z_2 = \sqrt{30^2 + 40^2} = 50 \text{ ohms.}$$

The power factor of branch ② is $\cos \theta_2 = \frac{R_2}{Z_2} = \frac{30}{50} = 0.60$ and the phase angle is 53.1°.

The current vectors for both branches are shown in figure 11-9 (B).

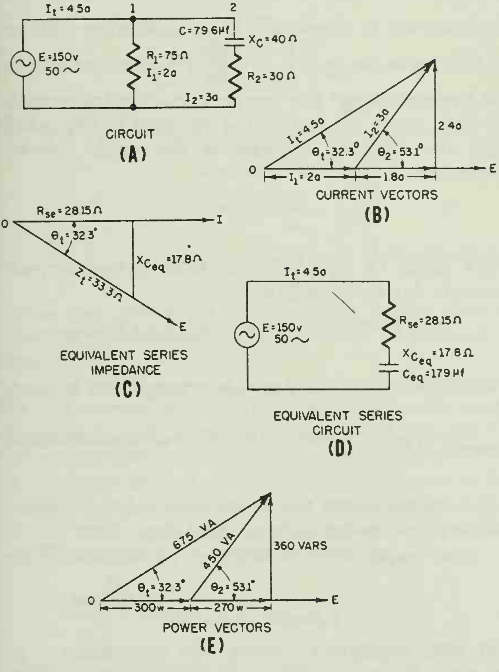
The current in branch ① is $I_1 = \frac{E}{Z_1} = \frac{150}{75} = 2$ amperes, and is a portion of the base of the equivalent right triangle in line with the horizontal reference voltage, *OE*. This current is in phase with the applied voltage because there is no reactance present in branch ①

The current in branch ② is

$$I_2 = \frac{E}{Z_2} = \frac{150}{50} = 3 \text{ amperes,}$$

and is the hypotenuse of the right triangle, the base of which is $I_2 \cos \theta_2 = 3$ (cos 53.1 = 0.6) = 1.8 amperes (energy current) and the altitude of which is $I_2 \sin \theta_2 = 3$ (sin 53.1 = 0.8) = 2.4 amperes (nonenergy current). The total current is the vector sum of I_1 and I_2 and is the hypotenuse of the equivalent right triangle, the base of which is the arithmetic sum of the current in branch①and the energy component of current in branch②, or 2 + 1.8 = 3.8 amperes. The altitude of the equivalent right triangle is equal to the nonenergy current in branch② or 2.4 amperes. The total current in the parallel circuit is

$$I_t = \sqrt{(3.8)^2 + (2.4)^2} = 4.5 \text{ amperes.}$$



CIRCUIT
(A)

CURRENT VECTORS
(B)

EQUIVALENT SERIES IMPEDANCE
(C)

EQUIVALENT SERIES CIRCUIT
(D)

POWER VECTORS
(E)

Figure 11-9.—Two-branch R-C circuit with currents out of phase by an angle of 53.1°.

The phase angle, θ_t between the total circuit current and the applied voltage is the angle whose cosine is $\frac{3.8}{4.5} = 0.845$. This angle is approximately 32.3°. Thus, the total current leads the applied voltage by an angle of 32.3°.

The total impedance of the parallel circuit is

$$Z_t = \frac{E}{I_t} = \frac{150}{4.5} = 33.3 \text{ ohms}$$

and is the hypotenuse of the impedance triangle (fig. 11-9 (C)). The base of the triangle is

$$R_{se} = Z_t \cos \theta_t = 33.3 (\cos 32.3° = 0.845) = 28.15 \text{ ohms}$$

of resistance and is in line with the horizontal current reference vector for the equivalent series circuit (fig. 11-9 (D)). The altitude of the triangle is

$$X_{C_{eq}} = Z_t \sin \theta_t = 33.3 (\sin 32.3° = 0.534) = 17.8 \text{ ohms}$$

of capacitive reactance. The capacitance of the equivalent series circuit at the operating frequency of 50 cycles per second is

$$C_{eq} = \frac{10^6}{2\pi f X_C} = \frac{10^6}{6.28 \times 50 \times 17.8} = 179 \text{ microfarads.}$$

The power relations are indicated in the triangles of figure 11-9 (E). The apparent power of the total circuit is EI_t = 150 x 4.5 = 675 volt-amperes and is the hypotenuse of the equivalent right triangle representing the total parallel circuit.

The true power in branch①is

$$I_1^2 R_1 = 2^2 \times 75 = 300 \text{ watts.}$$

The true power in branch②is

$$I_2^2 R_2 = 3^2 \times 30 = 270 \text{ watts.}$$

The total true power is

$$300 + 270 = 570 \text{ watts,}$$

and is the base of the equivalent right triangle for the entire circuit. The reactive power in the total circuit—that is, the reactive power of branch②—is

$$I_2^2 X_C = 3^2 \times 40 = 360 \text{ VARS,}$$

and is the altitude of the equivalent triangle.

The apparent power in branch①is equal to the true power because the power factor is unity. The apparent power in branch②is EI_2 = 150 x 3 = 450 volt-amperes and is the hypotenuse of the power triangle for this branch. The true power of 270 watts in branch②is the base of this triangle. The reactive power of 360 VARS in branch②is the altitude of the triangle. The power factor for branch ② is $\cos \theta_2 = \frac{\text{true power}}{\text{apparent power}} = \frac{270}{450} = 0.60$, and the phase angle for branch② is $\theta_2 = 53.1°$.

PARALLEL CIRCUITS CONTAINING L, R, AND C

Inductance in an a-c circuit causes the current to lag behind the applied voltage. Transformers and induction motors are essentially inductive in nature and the power factor, especially on light loads (as contrasted with full loads), is relatively low.

Most circuits that supply electric power from the source to the consumer transmit the power at relatively high voltage and low current in order to keep the I^2R loss in the transmission lines satisfactorily low. Transformers at the point of utilization reduce the voltage to the proper value to operate the equipment.

Capacitance in a-c circuits causes the current to lead the applied voltage and when placed in parallel with inductive components can produce a neutralizing effect so that lagging currents can be brought into phase with the applied voltage or may be made to lead the applied voltage, depending on the relative magnitude of the capacitance and inductance in parallel.

The true power of a circuit is $P = EI \cos \theta$; and for any given amount of power to be transmitted, the current, I, varies inversely with the power factor, $\cos \theta$. Thus, the addition of capacitance in parallel with inductance will, under the proper conditions, improve the power factor (make nearer unity power factor) of the circuit and make possible the transmission of electric power with reduced line loss and improved voltage regulation.

Current Vectors

In the example of figure 11-10, the parallel circuit contains three branches. Branch①contains a 30-ohm resistor. Branch ②consists of an inductor of 0.0612 henry and a resistor of 6.6 ohms. Branch ③ contains a capacitance of 44.3 microfarads having negligible losses. The parallel circuit is shown in figure 11-10 (A). The current vectors are shown in figure 11-10 (B).

The current in branch①is

$$I_{1en} = \frac{E}{R_1} = \frac{120}{30} = 4 \text{ amperes.}$$

The corresponding 4-ampere vector in figure 11-10 (B), is drawn in the same horizontal reference line as the voltage vector because the phase angle between the current and voltage in this branch is zero.

The inductive reactance of branch ② at the operating frequency of 60 cycles per second is

$$X_L = 2\pi f L = 6.28 \times 60 \times 0.0612 = 23.1 \text{ ohms.}$$

The impedance of branch②is

$$Z_2 = \sqrt{R_2^2 + X_L^2} = \sqrt{(6.6)^2 + (23.1)^2} = 24 \text{ ohms.}$$

The current in branch②, at the operating voltage of 120 volts, is $I_2 = \frac{E}{Z_2} = \frac{120}{24} = 5$ amperes and is the hypotenuse of the current triangle for branch ②. The angle by which the current in branch② lags the applied voltage is the angle whose cosine is

$$\frac{R_2}{Z_2} = \frac{6.6}{24} = 0.275.$$

This angle is $\theta_2 = 74°$. The base of the current triangle for branch②is

$$I_{2\,en} = I_2 \cos 74° = 5\,(\cos 74° = 0.275) = 1.38 \text{ amperes.}$$

The altitude of the current triangle for branch ②is

$$I_{2\,nonen} = I_2 \sin 74° = 5(\sin 74° = 0.962) = 4.8 \text{ (approx.) amperes}$$

and extends below the horizontal voltage reference vector to indicate current lag.

The capacitive reactance in branch ③ is

$$X_c = \frac{1}{2\pi f C} = \frac{1}{6.28 \times 60 \times 44.3 \times 10^{-6}} = 60 \text{ ohms,}$$

and with negligible losses, the impedance, Z_3, is also 60 ohms. The current in branch ③is

$$I_{3\,nonen} = \frac{E}{Z_3} = \frac{120}{60} = 2 \text{ amperes.}$$

The current in the capacitor branch leads the applied voltage by an angle of 90°. The non-energy component of the current in the inductive branch lags the applied voltage by an angle of 90°. Therefore, these two currents are 180° out of phase with each other, and the capacity current vector, I_3, extends upward

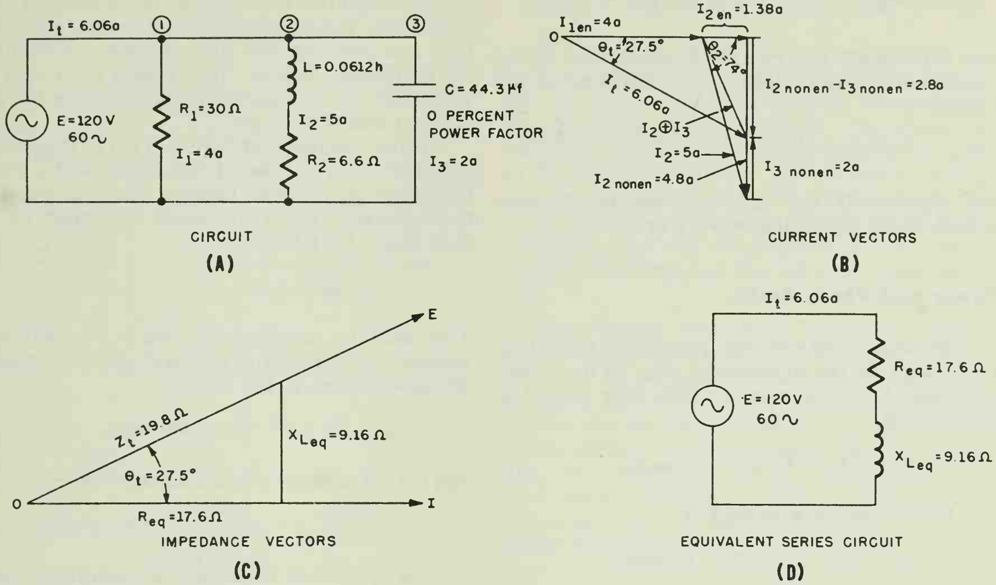

I_t = 6.06a
①
②
③
E=120 V
60∿
R_1=30Ω
I_1=4a
L=0.0612h
I_2=5a
R_2=6.6Ω
C=44.3μf
0 PERCENT POWER FACTOR
I_3=2a
CIRCUIT
(A)
O
I_{1en}=4a
I_{2en}=1.38a
θ_t=27.5°
θ_2=74°
I_t=6.06a
$I_2 \oplus I_3$
I_2=5a
I_{2nonen}=4.8a
$I_{2nonen}-I_{3nonen}$=2.8a
I_{3nonen}=2a
CURRENT VECTORS
(B)
E
Z_t=19.8Ω
θ_t=27.5°
X_{Leq}=9.16Ω
O
I
R_{eq}=17.6Ω
IMPEDANCE VECTORS
(C)
I_t=6.06a
R_{eq}=17.6Ω
E=120V
60∿
X_{Leq}=9.16Ω
EQUIVALENT SERIES CIRCUIT
(D)

Figure 11-10.—Parallel circuit containing L, R, and C.

from the lower extremity of the vector representing the nonenergy component of current in branch②.

The total current, I_t, in the parallel circuit is the vector sum of the currents in the three branches and is the hypotenuse of the equivalent current triangle, the base of which is the arithmetic sum of the energy components of the currents and the altitude of which is the algebraic sum of the nonenergy components of the currents. Thus, the total current is

$$I_t = \sqrt{(I_{1en} + I_{2en})^2 + (I_{2nonen} - I_{3nonen})^2}$$

$$= \sqrt{4 + (1.38)^2 + (4.8-2)^2}$$

$$= 6.06 \text{ amperes.}$$

The phase angle, θ_t, between the total current and the applied voltage is the angle whose cosine is the ratio of the sum of the energy components of the currents in all the branches to the total current. Thus,

$$\cos \theta_t = \frac{4 + 1.38}{6.06} = 0.888.$$

$$\theta_t = 27.5°,$$

and the total circuit current lags the applied voltage by an angle of 27.5°.

Equivalent Series Impedance

The total impedance of the parallel circuit (fig. 11-10 (A)) is equal to the total circuit voltage divided by the total circuit current, or

$$Z_t = \frac{E}{I_t} = \frac{120}{6.06} = 19.8 \text{ ohms,}$$

and is the hypotenuse of the impedance triangle (fig. 11-10 (C)). This triangle represents the impedance relations existing in the equivalent series circuit (fig. 11-10 (D)). The phase angle, θ_t, of the equivalent series circuit has the same magnitude as the phase angle between the total circuit current and the applied voltage across the parallel circuit. The impedance of the equivalent series circuit has the same magnitude as the total impedance of the parallel circuit. The base of the triangle is

$$R_{eq} = Z_t \cos\theta_t = 19.8\ (\cos 27.5^\circ = 0.889) = 17.6 \text{ ohms},$$

and represents the resistive component of the equivalent series circuit. The altitude of the triangle is

$$X_{L_{eq}} = Z_t \sin\theta_t = 19.8\ (\sin 27.5^\circ = 0.462) = 9.16 \text{ ohms},$$

and represents the inductive reactance component of the equivalent series circuit.

Power and Power Factor

The true power of the parallel circuit (fig. 11-10 (A)) is the arithmetic sum of the power absorbed in each branch. The true power in branch ① is

$$P_1 = I_1^2 R_1 = 4^2 \times 30 = 480 \text{ watts}.$$

The true power in branch ② is

$$P_2 = I_2^2 R_2 = 5^2 \times 6.6 = 165 \text{ watts}.$$

The true power in branch ③ is negligible since the power factor of the capacitor is assumed to be zero. The total true power is

$$480 + 165 = 645 \text{ watts}.$$

The total apparent power of the parallel circuit is the product of the total circuit current and the applied voltage. Thus, the apparent power is

$$EI_t = 120 \times 6.06 = 727.2 \text{ volt-amperes}.$$

The parallel circuit power factor is the ratio of the total true power to the total apparent power. Thus, the circuit power factor is

$$\cos\theta_t = \frac{\text{true power}}{\text{apparent power}} = \frac{645}{727.2} = 0.888.$$

Power-Factor Correction

Power-factor correction in parallel circuits is accomplished by placing a capacitor of the proper size in parallel with the circuit at the point where the power-factor correction is to be effected. The leading current of the capacitor branch supplies the lagging component of current in the inductive portion of the parallel circuit and reduces the line current accordingly. As mentioned before, this action improves the efficiency of transmission by reducing the line current and I^2R losses.

In the example of figure 11-11, the load is rated at 10 amperes, 1,000 volts, and a power factor of 50 percent lagging (the current lags the voltage). The true power absorbed by the load (fig. 11-11 (A)) is

$$P = EI\cos\theta = 1{,}000 \times 10 \times 0.5 = 5{,}000 \text{ watts}.$$

The load is supplied through a line having a resistance of 20 ohms and negligible reactance. The power loss in the line is

$$I^2R = 10^2 \times 20 = 2{,}000 \text{ watts},$$

and the efficiency of transmission is

$$\frac{\text{output}}{\text{output} + \text{losses}} = \frac{5{,}000}{5{,}000 + 2{,}000} = 71.4 \text{ percent}.$$

If a 1,000-volt capacitor of negligible losses supplying a leading current of 8.66 amperes is placed in parallel with the inductive load (fig. 11-11 (B)), the total line current will be reduced from 10 amperes to 5 amperes.

The current vectors are shown in figure 11-11 (C). The nonenergy component of the current in the inductive branch is $I_{nonen} = I \sin\theta = 10\ (\sin 60^\circ = 0.866) = 8.66$ amperes (lagging) and is 180° out of phase with the capacitor current of 8.66 amperes (leading). These currents circulate between the capacitor and the inductive load and do not enter the line. The vector sum of the capacitor current and the total inductive load current is equal to the line current ($I_t = 5$ amperes), and in the vector diagram is represented as the diagonal of the parallelogram of which the 2 branch currents are the sides. The line current vector, I_t, is in the same horizontal reference as the load voltage vector, indicating that the line current is in phase with the voltage applied to the parallel combination of the inductive load and the capacitor.

The reduction in line current from 10 to 5 amperes reduces the line loss from 2,000 watts to $5^2 \times 20 = 500$ watts and increases the efficiency of transmission from 71.4 percent to $\frac{5{,}000}{5{,}000 + 500} = 91$ percent. Thus, the improvement in efficiency of operation of the line and load is

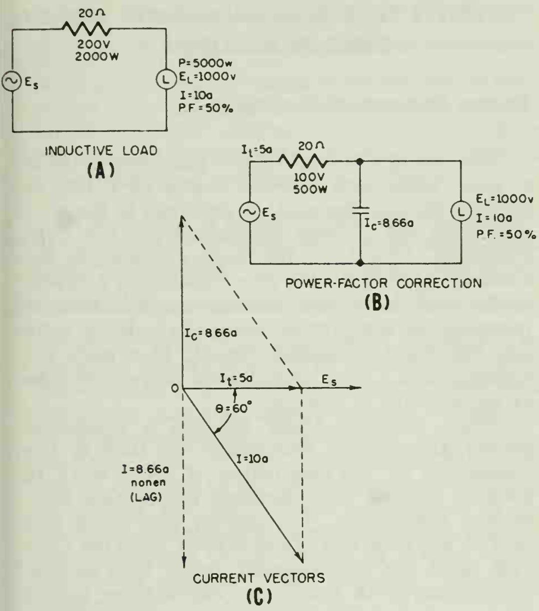


Figure 11-11.—Power-factor correction.

demonstrated. The condition represented involves an interchange of energy between the inductive and capacitive branches known as parallel resonance and is described in the training manual, *Basic Electronics*, NavPers 10087, chapter 1, on the subject of resonance in *L-R-C* circuits.

VOLTAGE REDUCTION WITH RESISTANCE

The example of figure 11-12 illustrates the advantages and disadvantages of controlling the voltage on a load by means of resistance and inductance and also the effect of power-factor correction on the circuit efficiency.

In figure 11-12 (A), the voltage applied to the load is reduced from 100 volts to 50 volts through the action of the dropping resistor. The circuit current is 10 amperes, and the voltage across the dropping resistor is 50 volts. With this arrangement, the input power to the circuit is divided equally between the resistor and the load, and the circuit efficiency $\left(\frac{\text{output}}{\text{output} + \text{losses}} \times 100\right)$ is $\frac{500}{500 + 500} \times 100 = 50$ percent. This arrangement represents an inefficient method of voltage reduction.

VOLTAGE REDUCTION WITH INDUCTANCE

In figure 11-12 (B), the voltage applied to the load is reduced to 50 volts through the action of the series inductor. Neglecting the relatively small losses in the inductor, the circuit efficiency remains high compared to the efficiency of the previous circuit, but the series inductor lowers the power factor from unity (100 percent) to 50 percent. The circuit current is still 10 amperes, and the accompanying line loss between the source and the inductor unnecessarily high.

The voltage vectors for the *L-R* circuit are shown in figure 11-12 (C). The load voltage of 50 volts is the base of the right triangle and is in phase with the load current. The voltage drop across the inductor is 86.6 volts and is the altitude of the voltage triangle. The source voltage, $E_S = 100$ volts, is the vector sum of the load voltage and the inductor voltage and is the hypotenuse of the voltage triangle. The circuit power factor is

$$\cos\theta = \frac{E_{\text{load}}}{E_{\text{source}}} = \frac{50}{100} = 0.5,$$

and

$$\theta = 60°.$$

In figure 11-12 (D), the circuit power factor is improved to unity by the addition of a capacitor of negligible losses which supplies a leading current of 8.66 amperes. This current supplies the nonenergy component of the current in the branch containing the inductor and load, and reduces the line current from 10 amperes to 5 amperes.

The current vectors are shown in figure 11-12 (E). The capacitor current of 8.66 amperes is represented by the vector extending above the horizontal voltage reference vector to indicate a lead of 90°. The inductor branch (load) current extends below the horizontal at an angle of 60° to indicate lag. The vector sum of these currents is the diagonal of the parallelogram of which the branch currents are the sides, and is a horizontal vector of 5 amperes in phase with the source voltage. Thus, the power factor of the parallel circuit is unity and the line current is reduced from 10 amperes to 5 amperes.

ADVANTAGES OF INDUCTIVE ARRANGEMENT WITH POWER-FACTOR CORRECTION

In the example under consideration, voltage reduction with a series inductor and a shunt capacitor provides a means of supplying a 50-volt 10-ampere load from a 100-volt source with only the small losses associated with the reactive components. The line current is kept to the minimum value required to supply the 500-watt load, and the circuit efficiency is high. Inductive control alone provides a means of reducing the load voltage by changing the phase of the applied voltage with respect to the load voltage. The addition of the capacitor reduces the current in the line without altering the load current, and thus reduces the line losses; at the same time the circuit power factor is increased to unity. In most circuits it is not economical to improve the power factor to unity, but to improve it, for example, from 50 percent lagging to 85 percent lagging. The reduction in line losses is most pronounced in this range and any further reduction in losses may not justify the added expense of the capacitance required to further improve the power factor in the range from 85 percent lagging to unity.

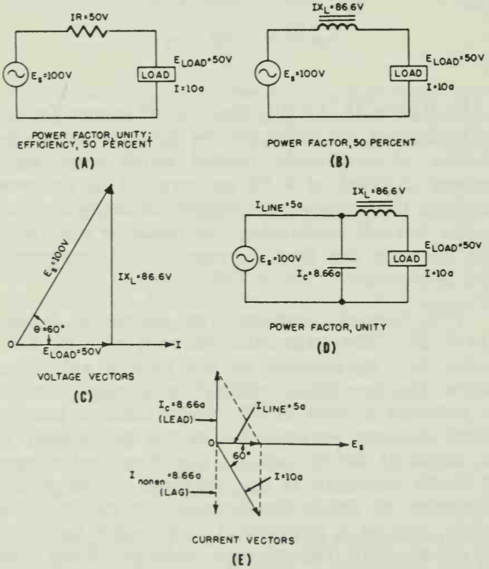


Figure 11-12.—Voltage reduction and power-factor correction.

EFFECTIVE RESISTANCE—NONUSEFUL ENERGY LOSSES IN A-C CIRCUITS

Energy Concept of Resistance

The energy stored in the magnetic field of a pure inductance, as the result of a rise in current through the coil, is returned to the circuit when the current decreases and the field collapses. Similarly, the energy stored in the electric field of a pure capacitance, as a result of the rise in voltage across the capacitor, is returned to the circuit when the voltage falls and the field collapses. Hence, in a pure inductance and a pure capacitance there is no loss or expenditure of energy.

When current flows through a conductor having appreciable resistance the flow is accompanied by the generation of heat. Work is done in moving the electrons through the conductor resistance. The energy converted into heat is not returned to the circuit when the current falls, but is expended rather than stored. Thus, energy is stored periodically in inductance and capacitance but always expended in resistance.

Because resistance is the only circuit quality capable of expending electrical energy, all energy expended in any circuit can be identified in electrical terms, one factor of which is effective resistance. The effective resistance, R_{ac}, of any circuit may be defined as the ratio of the true power absorbed by the circuit to the square of the effective current flowing in the circuit, or $R_{ac} = \frac{P}{I^2}$. When the power is expressed in watts and the current is expressed in amperes, the effective resistance will be in ohms. The d-c circuit resistance as measured by an ohmmeter or d-c bridge may be considerably lower than the effective a-c resistance as calculated from the readings on a wattmeter and an ammeter.

For example, assume that a motor draws 1 kilowatt from a 110-volt source. The input current is 10 amperes. The effective resistance between the motor terminals is

$$R_{ac} = \frac{P}{I^2} = \frac{1{,}000}{(10)^2} = 10 \text{ ohms}.$$

The d-c resistance measured between the motor terminals, for example with an ohmmeter, is

0.5 ohm. Thus, in this example the effective a-c resistance is $\frac{10}{0.5}$, or 20 times the d-c resistance. Most of the energy taken from the line is converted into mechanical energy and is not returnable to the electric circuit; hence, it is represented electrically as being expended in an effective a-c resistance of 10 ohms.

The source of power for the motor is unaware of the manner in which the motor expends the electrical energy. To the source, the motor appears as an impedance, $Z = \frac{E}{I} = \frac{110}{10} = 11$ ohms, having a resistive component of 10 ohms. The nature of the various energy conversions taking place inside the motor is important only when the motor itself is being analyzed. From this point of view a motor, electric light, loudspeaker, electron tube, or any other electrical device can be pictured as an equivalent electric circuit containing the fundamental components of inductance, capacitance, and resistance. The energy expended in the circuit is always interpreted in terms of the effective resistance component.

The energy expended in any electrical device may be divided into two parts: (1) That which is converted into useful form; and (2) that which is not useful. No machine has been built that is capable of perfect conversion—that is, one in which there are no losses. In the motor, for example, there are friction losses in the bearings and heat losses in the windings as a result of the current flow through the resistance which they possess.

The number of possible nonuseful losses in a-c circuits is much greater than in d-c circuits. These include: (1) ohmic-resistance loss, (2) skin-effect loss, (3) eddy-current loss, (4) dielectric loss, (5) magnetic-hysteresis loss, (6) corona loss, and (7) radiation loss.

Effective Resistance of Conductors

The effective (a-c) resistance of electrical conductors is frequently higher than their d-c resistance especially when they are embedded in iron slots, as in the case of motor and generator armatures; and when they are being used in high-frequency circuits, as in radio transmitters and receivers.

Direct current is distributed uniformly throughout the cross-sectional area of a homogeneous conductor. For example, if a conductor having a cross-sectional area of 1,000 circular mils is carrying one ampere of direct current then one-thousandth of an ampere (one milliampere) is flowing in each circular mil of cross-sectional area. However, when the current in the conductor varies in amplitude, this uniform distribution throughout the conductor cross section is no longer obtained. The accompanying magnetic field is strongest near the center of the conductor and weaker at the circumference. The varying field induces a voltage in the conductor that opposes the change in current. The voltage induced in that portion of the conductor near the center is greater than the voltage induced in the outer surface of the conductor. The total opposition to the current flow includes the effect of this induced e.m.f. and is greater near the center of the conductor than at the surface. Therefore, the current divides inversely with the opposition—more of the current flowing near the circumference, and less near the center of the conductor.

The overall result of this action is a decrease in the available area of cross section to conduct the current and an increase in conductor resistance. The decrease in area and increase in resistance become pronounced at high frequencies, at high current densities, and at high magnetic flux densities. This action is called SKIN EFFECT. It represents the tendency of a-c conductors to carry the circuit current on the surface, or skin, of the conductors rather than uniformly throughout their cross section. As a result of this tendency, many electrical conductors are made of hollow tubing in order to save the added weight and expense of the unused central portion of the solid conductor. The effective a-c resistance of an isolated circular conductor varies approximately as the product of the square root of the frequency and the length of the conductor, and inversely as the conductor diameter.

Effective Resistance of Inductors

When a conductor is wound in the form of a coil, the current is concentrated on the inner sides of the turns and into an area much smaller than would be the case in an isolated straight conductor. This action results in a large increase in effective resistance. The area in which the current is concentrated decreases as the frequency increases, hence, effective resistance will increase with frequency. When two or more conductors carrying alternating current are so placed that the magnetic field of one reacts with the field of the other, the resultant field around each conductor is no longer uniform. The change in current distribution in a conductor due to the action of an alternating current in a nearby conductor is called PROXIMITY EFFECT.

The proximity effect decreases as the separation between conductors increases. Thus, to lower the effective resistance of radio frequency inductance coils, it is common practice to space the turns a distance equal to the diameter of the conductor. This decreases the reaction between magnetic fields of adjacent turns and permits the current to distribute itself over a larger area in the cross section of each turn.

The inductance of a hollow-core coil operating at a frequency of 60 cycles per second is increased many fold when a laminated core of soft silicon steel is inserted in the coil. This increase is due to the high permeability of the transformer-iron laminations. Thus, the skin effect is also increased due to the increased field strength. In addition to the increased skin effect in the coil, the effective a-c resistance is further increased because of the magnetic hysteresis loss in the iron. Thus, if the coil is connected to a constant-potential a-c source, the current in the coil will decrease when the iron core is inserted because of a small increase in effective resistance and a large increase in the coil reactance. If the laminated steel core is removed and a piece of steel shafting is inserted in the coil, the effective resistance is further increased due to the eddy-current losses and the larger hysteresis losses in the steel shaft. A wattmeter inserted in the coil circuit will indicate this increase in effective resistance by an increased deflection when the solid steel core is inserted in place of the laminated core.

Powdered iron cores are used in certain types of coils on frequencies as high as 100 megacycles in order to limit the effective resistance of the coil to a satisfactorily low value. The iron particles are separated from each other by an insulated coating and when compressed into cylindrical form and inserted in the coil the induced voltage in each iron particle is so small in relation to the resistance to the path for eddy currents that the accompanying heat loss is negligible. Eddy-current losses are reduced in generator and motor armature conductors of large size by laminating the conductors and insulating the adjacent laminations in a manner similar to that in which the iron of the armature core itself is laminated. Thus, the effective resistance of the armature conductors is reduced.

Effective Resistance of Capacitors

The equivalent circuits of a low-loss capacitor were described earlier in this chapter and the factors affecting the equivalent series resistance noted. The effective a-c resistance of a capacitor is equal to its equivalent series resistance and represents the factor which when multiplied by the square of the effective capacitor charging current will equal the power expended in heat in the capacitor circuit.

As mentioned previously, most of the heating is produced in solid dielectrics, and only a negligible amount is produced in the capacitor plates themselves. The dielectric heating is produced by dielectric displacement currents described in connection with figure 11-7. In most electrical circuits, dielectric heating is a nonuseful loss. However, in one commercial application, dielectric heating has been put to good use—that of facilitating the gluing together of stacks of laminated plywood. The plywood laminations are stacked between the plates of a capacitor and a moderately high-frequency voltage is applied across the plates. The resulting dielectric displacement currents heat the stack from the inside and the glue is quickly set—much more rapidly than in processes involving the external application of steam heat.

Corona Loss

Corona loss occurs as the result of the emission of electrons from the surface of electrical conductors at high potentials. It is dependent upon the curvature of the conductor surface, with most emission occurring from sharp points and the least emission occurring from surfaces having a large radius of curvature. Corona loss is frequently accompanied by a visual blue glow and an audible hissing sound as the electrons leak off the conductor surface into the atmosphere. Corona loss increases with voltage increase and decreases with increase in atmospheric pressure. This loss is held to a satisfactorily low value by (1) the use of large-diameter conductors, (2) not excessively high voltages, (3) smooth polished surfaces, (4) avoiding sharp points, bends, or turns, and (5) in some devices, for example, high-voltage capacitors, by the use of a compressed gas to retard the electron emission.

Radiation Loss

Radiation loss is not appreciable at power line frequencies, but in the field of communications this loss may become excessive. Power is radiated from transmitting antennas in the form of electric and magnetic fields, and its magnitude varies as the square of the antenna input current and as the so-called radiation resistance of the antenna. The transmission line that connects the transmitter and the antenna may, under certain circumstances, develop a radiation loss. This loss is discussed in chapter 10 of *Basic Electronics*, NavPers 10087, in connection with various types of transmission lines.

QUIZ

1. When resistive, inductive, and capacitive elements are connected in series,
   a. they lose their individual characteristics
   b. their individual characteristics remain unchanged
   c. the inductance component is always the largest
   d. the capacitive component is always the largest

2. In a circuit containing both X_C and X_L, if the difference between X_C and X_L increases, the total
   a. impedance decreases
   b. impedance increases
   c. impedance remains the same
   d. resistance increases

3. In a 60-cycle a-c circuit, with an inductor of 0.053 microhenry and a resistance of 50 ohms connected in series, the impedance would be
   a. 539 ohms
   b. 5.39 ohms
   c. 53.9 ohms
   d. 19.97 ohms

4. The effective resistance of a circuit may be defined as the ratio of the
   a. true power absorbed by the circuit to the square of the effective current flowing
   b. apparent power absorbed by the circuit to the square of the effective current flowing
   c. true power absorbed by the circuit to the square of the total resistance in the circuit
   d. apparent power absorbed by the circuit to the square of the total resistance in the circuit

5. In a series circuit, when X_C and X_L are equal,
   a. line voltage leads line current by an unknown $\angle\theta$
   b. line current leads line voltage by an unknown $\angle\theta$
   c. total impedance is minimum
   d. total impedance is maximum

6. To find true power, use the formula
   a. T.P. = E x I
   b. T.P. = E x I x cos $\angle\theta$
   c. T.P. = $E^2 \div$ I x cos $\angle\theta$
   d. T.P. = E x I x sin $\angle\theta$

7. A low-loss inductor has a low
   a. X_L at high frequencies
   b. current at low frequencies
   c. inductance
   d. resistance

8. The most inefficient method of voltage reduction, from the standpoint of power loss, is a/an
   a. capacitor in series with the load
   b. inductor in series with the load
   c. capacitor and an inductor in series with the load
   d. resistor in series with the load

9. The formula for finding the loss factor of a capacitor is the dielectric constant
   a. times the power factor
   b. divided by the power factor
   c. times the apparent power
   d. times the true power

10. A phase difference between E and I causes
   a. true power to increase
   b. apparent power to increase
   c. true power to decrease
   d. apparent power to decrease

11. The energy component of a current flowing in an R-L circuit is the current flowing through the
    a. inductor and resistor
    b. inductor
    c. resistor
    d. power source
12. Corona loss is the result of
    a. emission of electrons from the surface of a conductor
    b. electron collision inside a conductor
    c. overheating a high-frequency conductor
    d. none of the above
13. To find total true power in a parallel circuit, first find the true power in each branch and then
    a. add the power in all branches arithmetically
    b. add the power in all branches using the parallelogram method
    c. multiply the voltage times the current
    d. multiply the square of the current times the resistance
14. The hypotenuse of the power triangle represents
    a. true power
    b. VARS
    c. apparent power
    d. none of the above
15. To find a circuit's power factor in percent, use the formula
    a. $P.F. = \frac{AP}{TP} \times 100$
    b. $P.F. = \cos \angle\theta$
    c. P.F. = angle in degrees x 100
    d. $P.F. = \frac{E \times I \times \cos \angle\theta}{E \times I} \times 100$
16. Corona loss can be held to a satisfactory low value by
    a. avoiding sharp points, bends, and turns
    b. using low voltages
    c. using large diameter conductors
    d. all of the above
17. In a parallel circuit with a lagging power factor, to improve the power factor
    a. increase the inductance
    b. put an inductor in parallel with the rest of the circuit
    c. put a capacitor in parallel with the rest of the circuit
    d. decrease the resistance
18. The nonenergy component of an a-c circuit is
    a. true power
    b. reactive power
    c. apparent power
    d. none of the above
19. The formula for computing R-L-C in series is
    a. $Z = R_T + X_L + X_C$
    b. $Z = R + X_L - X_C$
    c. $Z^2 = R^2 + (X_L{}^2 - X_C{}^2)$
    d. $Z = R^2 + (X_L{}^2 - X_C{}^2)$
20. One radian is equal to
    a. $\frac{180}{2\pi}$
    b. 2π
    c. 1.414
    d. $\frac{360}{2\pi}$
21. Skin effect describes the tendency of
    a. d-c conductors to carry the circuit current on their surfaces
    b. a-c conductors to carry the circuit current on their surfaces
    c. both a-c and d-c conductors to carry the circuit current on their surfaces
    d. none of the above
22. The current in an a-c parallel circuit varies
    a. inversely with the cos $\angle\theta$
    b. directly with the cos $\angle\theta$
    c. inversely with the sine $\angle\theta$
    d. directly with the sine $\angle\theta$
23. In a circuit containing X_C and X_L, if X_C is larger,
    a. the voltage would lead the current
    b. the current would lead the voltage
    c. there would be no phase difference
    d. true power is maximum
24. The effective resistance of a capacitor is dissipated in heat in the
    a. positive capacitor plate
    b. negative capacitor plate
    c. dielectric
    d. leads connecting the capacitor in the circuit

CHAPTER 12

BASIC ELECTRICAL INDICATING INSTRUMENTS

In the field of electricity, as in all the other physical sciences, accurate quantitative measurements are essential. This involves two important items—numbers and units. Simple arithmetic is used in most cases, and the units are well-defined and easily understood. The standard units of current, voltage, and resistance as well as other units are defined by the National Bureau of Standards. At the factory, various instruments are calibrated by comparing them with established standards.

The technician commonly works with ammeters, voltmeters, ohmmeters, and electron-tube analyzers; but he may also have many occasions to use wattmeters, watt-hour meters, power-factor meters, synchroscopes, frequency meters, and capacitance-resistance-inductance bridges.

Electrical equipments are designed to operate at certain efficiency levels. To aid the technician in maintaining the equipment, technical instruction books and sheets containing optimum performance data, such as voltages and resistances, are prepared for each Navy equipment.

To the technician, a good understanding of the functional design and operation of electrical instruments is important. In electrical service work one or more of the following methods are commonly used to determine if the circuits of an equipment are operating properly.

1. Use an ammeter to measure the amount of current flowing in a circuit.
2. Use a voltmeter to determine the voltage existing between two points in a circuit.
3. Use an ohmmeter or megger (megohmmeter) to measure circuit continuity and total or partial circuit resistance.

The technician may also find it necessary to employ a wattmeter to determine the total POWER being consumed by certain equipments. If he wishes to measure the ENERGY consumed by certain equipments or certain circuits, a watt-hour of kilowatt-hour meter is used.

For measuring other quantities such as power factor and frequency, which will be treated in a later chapter, the technician employs the appropriate instruments. In each case the instrument indicates the value of the quantity measured, and the technician interprets the information in a manner that will help him understand the way the circuit is operating. Occasionally the technician will need to determine the value of a capacitor or an inductor. Inductance or capacitance bridges may be employed for this purpose.

Although in this chapter the discussion is confined largely to d-c instruments, some of the instruments discussed may be used with alternating as well as direct current. Alternating-current instruments are treated in chapter 17.

A thorough understanding of the construction, operation, and limitations of the basic types of electrical measuring instruments, coupled with the theory of circuit operation, is most essential in servicing and maintaining electrical equipment.

D'Arsonval Meter

CONSTRUCTION

The stationary permanent-magnet moving-coil meter is the basic movement used in most measuring instruments for servicing electrical, especially d-c, equipment. This type of movement is commonly called the D'Arsonval movement because it was first employed by the Frenchman D'Arsonval in making electrical measurements.

The basic D'Arsonval movement consists of a stationary permanent magnet and a movable coil. When current flows through the coil the resulting magnetic field reacts with the magnetic field of the permanent magnet and causes the coil to rotate. The greater the amount of current flow through the coil the stronger the magnetic field produced and the stronger this field the greater the rotation of the coil. In order to determine the amount of current flow a means must be provided to indicate the amount of coil rotation. Either of two methods may be used—(1) the pointer arrangement, and (2) the light and mirror arrangement. In the pointer arrangement, one end of the pointer is fastened to the rotating coil and as the coil turns the pointer also turns. The other end of the pointer moves across a graduated scale and indicates the amount of current flow. A disadvantage of the pointer arrangement is that it introduces the problem of coil balance, especially if the pointer is long. An advantage of this arrangement is that it permits overall simplicity. The use of a mirror and a beam of light simplifies the problem of coil balance. When this arrangement is used to measure the turning of the coil, a small mirror is mounted on the supporting ribbon (fig. 12-1) and turns with the coil. An internal light source is directed to the mirror, and then reflected to the scale of the meter. As the moving coil turns, so does the mirror, causing the light reflection to move over the scale of the meter. The movement of the reflection is proportional to the movement of the coil, thus the amount of current being measured by the meter is indicated.

A simplified diagram of one type of stationary permanent-magnet moving-coil instrument is shown in figure 12-1. Such an instrument is commonly called a GALVANOMETER. The galvanometer indicates very small amounts (or the relative amounts) of current or voltage, and is distinguished from other instruments used for the same purpose in that the movable coil is suspended by means of metal ribbons instead of by means of a shaft and jewel bearings.

The movable coil of the galvanometer in figure 12-1 is suspended between the poles of the magnet by means of thin flat ribbons of phospher bronze. These ribbons provide the conducting path for the current between the circuit under test and the movable coil. They also provide the restoring force for the coil. The restoring force, exerted by the twist in the ribbons, is the force against which the driving force of the coil's magnetic field (to be described later) is balanced in order to obtain a measurement of the current strength. The ribbons thus tend to oppose the motion of the coil, and will twist through an angle that is proportional to the force applied to the coil by the action of the coil's magnetic field against the permanent field. The ribbons thus restrain or provide a counter force, for the magnetic force acting on the coil. When the driving force of the coil current is removed, the restoring force returns the coil to its zero position.

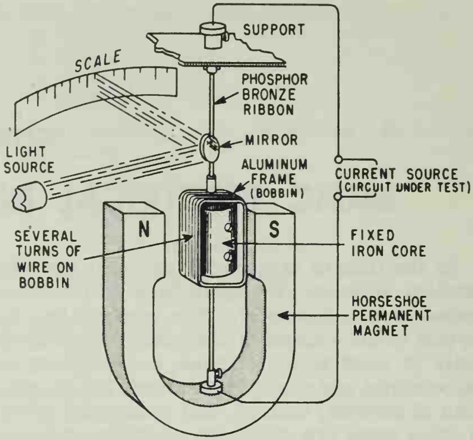

SUPPORT
SCALE
PHOSPHOR BRONZE RIBBON
MIRROR
LIGHT SOURCE
ALUMINUM FRAME (BOBBIN)
CURRENT SOURCE (CIRCUIT UNDER TEST)
N
S
SEVERAL TURNS OF WIRE ON BOBBIN
FIXED IRON CORE
HORSESHOE PERMANENT MAGNET

Figure 12-1.—Simplified diagram of a galvanometer.

If a beam of light and mirrors are used, the beam of light is swept to the right or left across a central-zero translucent screen (scale) having uniform divisions. If a pointer is used, the pointer is moved in a horizontal plane to the right or left across a central-zero scale having uniform divisions. The direction in which the beam of light or the pointer moves depends on the direction of current through the coil.

This instrument is used to measure minute current as, for example, in bridge circuits. In modified form, the basic D'Arsonval movement has the highest sensitivity of any of the various types of meters in use today.

OPERATING PRINCIPLE

In order to understand the operating principle of the D'Arsonval meter it is first necessary to consider the force acting on a current-carrying conductor placed in a magnetic field. The magnitude of the force is proportional to the product of the magnitudes of the current and the field strength. The field is established between the poles of a U-shaped permanent magnet and is concentrated through the conductor by means of a soft-iron stationary member mounted between the poles to complete the magnetic circuit. The conductor is made movable by shaping it in the form of a closed loop and mounting it between fixed pivots so that it is free to swing about the fixed iron member between the poles of the magnets. A convenient method of determining the direction of motion of the conductor is by the use of the RIGHT-HAND MOTOR RULE FOR ELECTRON FLOW (fig. 12-2).

To find the direction of motion of a conductor, the thumb, first finger, and second finger of the right hand are extended at right angles to each other, as shown. The first finger is pointed in the direction of the flux (toward the south pole) and the second finger is pointed in the direction of electron flow in the conductor. The thumb then points in the direction of motion of the conductor with respect to the field. The conductor, the field, and the force are mutually perpendicular to each other.

The force acting on a current-carrying conductor in a magnetic field is directly proportional to the field strength of the magnet, the active length of the conductor, and the intensity of the electron flow through it. Thus,

$$F = \frac{8.85 \times BLI}{10^8},$$

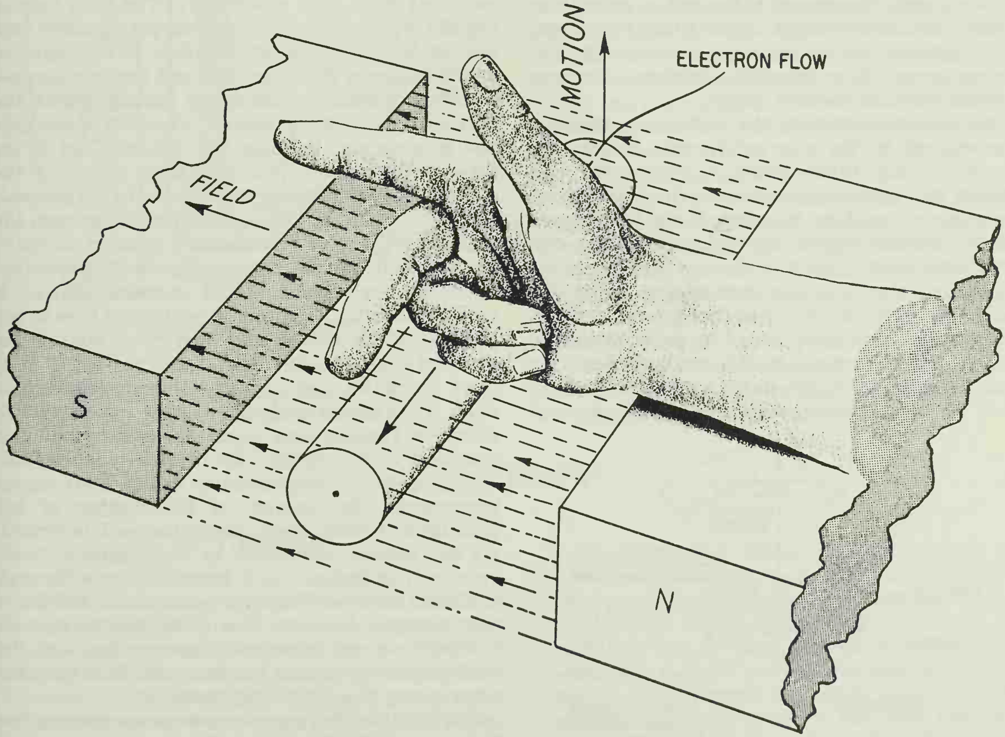


Figure 12-2.—Right-hand motor rule.

where F is the force in pounds, B the flux density in lines per square inch, L the active length of the conductor in inches, and I the current in amperes.

In the D'Arsonval-type meter, the length of the conductor is fixed and the strength of the field between the poles of the magnet is fixed. Therefore, any change in I causes a proportionate change in the force acting on the coil.

The principle of the D'Arsonval movement may be more clearly shown by the use of the simplified diagram (fig. 12-3) of the D'Arsonval movement commonly used in d-c instruments. In the diagram, only one turn of wire is shown; however, in an actual meter movement many turns of fine wire would be used, each turn adding more effective length to the coil. The coil is wound on an aluminum frame or bobbin, to which the pointer is attached. Oppositely wound hairsprings (one of which is shown in fig. 12-3), are also attached to the bobbin, one at either end. The circuit to the coil is completed through the hairsprings. In addition to serving as conductors, the hairsprings serve as the restoring force that returns the pointer to the zero position when no current flows.

As has been stated, the deflecting force is proportional to the current flowing in the coil. The deflecting force tends to rotate the coil against the restraining force of the hairspring. The angle of rotation is proportional to the force that the spring exerts against the moving coil (within the elastic limit of the spring). When the deflecting force and the restraining force are equal, the coil and the pointer cease to move. Because the restoring force is proportional to the angle of deflection, it follows that the driving force, and the current in the coil, are proportional to the angle of deflection. When current ceases to flow in the coil, the driving force ceases, and the restoring force of the springs returns the pointer to the zero position.

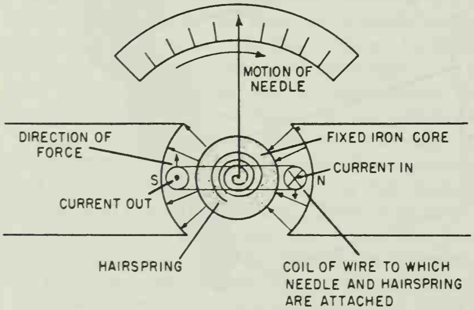


Figure 12-3.—D'Arsonval movement.

If the current through the single turn of wire is in the direction indicated (away from the observer on the right-hand side and toward the observer on the left-hand side), the direction of force, by the application of the right-hand motor rule, is upward on the left-hand side and downward on the right-hand side. The direction of motion of the coil and pointer is clockwise. If the current is reversed in the wire, the direction of motion of the coil and pointer is reversed.

A detailed view of the basic D'Arsonval movement, as commonly employed in ammeters and voltmeters, is shown in figure 12-4. This instrument is essentially a MICROAMMETER because the current necessary to activate it is of the order of 1 microampere. The principle of operation is the same as that of the simplified versions discussed previously. The iron core is rigidly supported between the pole pieces and serves to concentrate the flux in the narrow space between the iron core and the pole piece—in other words, in the space through which the coil and the bobbin moves. Current flows into one hairspring, through the coil, and out of the other hairspring. The restoring force of the spiral springs returns the pointer to the normal, or zero, position when the current through the coil is interrupted. Conductors connect the hairsprings with the outside terminals of the meter.

If the instrument is not damped—that is, if viscous friction or some other type of loss is not introduced to absorb the energy of the moving element—the pointer will oscillate for a long time about its final position before coming to rest. This action makes it nearly impossible to obtain a reading and some form of damping is necessary to make the meter practicable. Damping is accomplished in many D'Arsonval movements by means of the motion of the aluminum bobbin upon which the coil is wound. As the bobbin oscillates in the magnetic field, an e.m.f. is induced in it because it cuts through the lines of force. Therefore, according to Lenz's law, induced currents flow in the bobbin in such a direction as to oppose the motion, and the bobbin quickly comes to rest in the final position after going beyond it only once.

In addition to factors such as increasing the flux density in the air gap, the overall sensitivity of the meter can be increased by the use of a lightweight rotating assembly (bobbin, coil, and

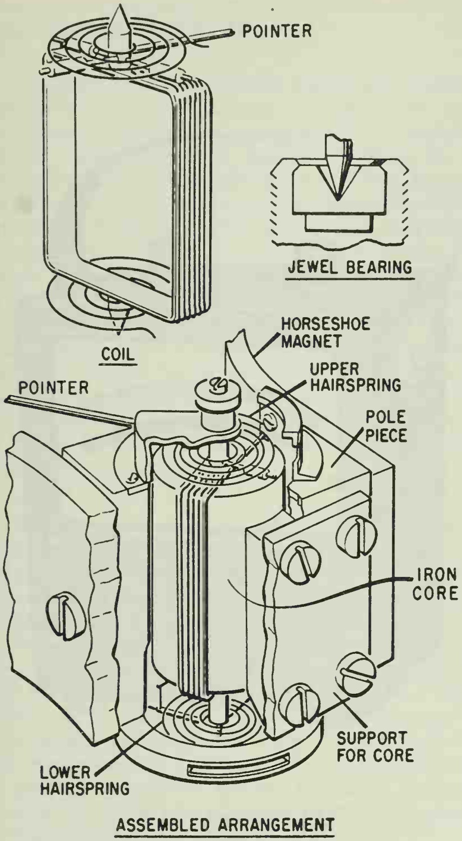


Figure 12-4.—Detailed view of basic D'Arsonval movement.

pointer) and by the use of jewel bearings as shown.

While D'Arsonval-type galvanometers are useful in the laboratory for measurements of extremely small currents, they are not portable, compact or rugged enough for use in the maintenance of military equipment. The Weston meter movement is used instead.

The Weston meter uses the principles of the D'Arsonval galvanometer, but it is portable, compact, rugged and easy to read. In the Weston meter the coil is mounted on a shaft fitted between two permanently mounted jewel bearings. A lightweight pointer is attached to and turns with the coil; the pointer indicates the amount of current flow. Figure 12-5 (A) illustrates this movement.

Balance springs on each end of the shaft exert opposite turning forces on the coil. By adjusting the tension of one spring, the meter pointer may be adjusted to read zero on the meter scale. Since temperature change affects both coil springs equally, this factor can be discounted. As the meter coil turns, one spring tightens to provide a restoring force; at the same time the other spring releases its tension. In addition to providing tension, the springs are also used as conductors to carry current from the meter terminals to the moving coil.

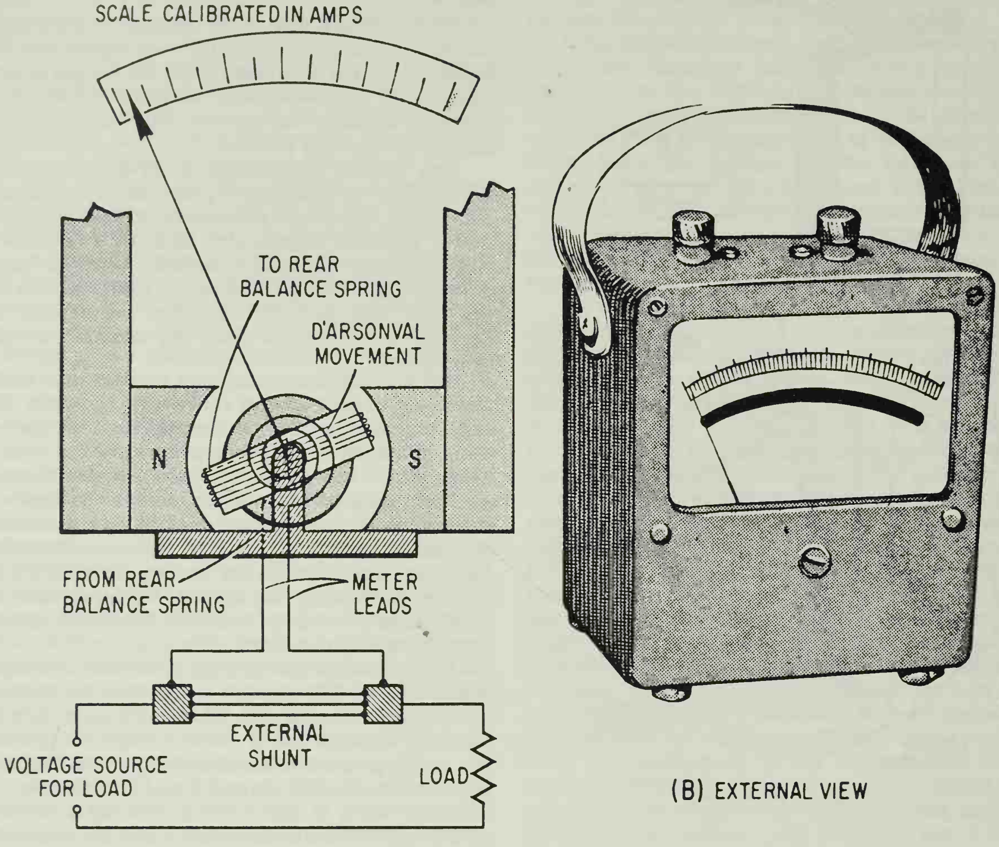
In order that the turning force will increase uniformly as the current increases, the horseshoe magnet poles are shaped to form semicircles. The amount of current required to turn the meter pointer to full-scale deflection depends upon the magnet's strength and the number of turns of wire in the moving coil. This amount of current is the ammeter's MAXIMUM ALLOWABLE AMOUNT. A further increase of meter current would damage the meter.

Ammeter

CONSTRUCTION

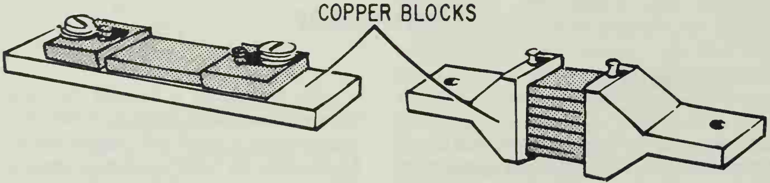
The small size of the wire with which an ammeter's movable coil is wound places severe limits on the current that may be passed through the coil. Consequently, the basic D'Arsonval movement discussed thus far may be used to indicate or measure only very small currents—for example, microamperes (10^{-6} amperes) or milliamperes (10^{-3} amperes), depending on meter sensitivity.

To measure a larger current, a shunt must be used with the meter. A shunt is a heavy low-resistance conductor connected across the meter terminals to carry most of the load current. This shunt has the correct amount of resistance to cause only a small part of the total circuit current to flow through the meter coil. The meter current is proportional to the load current. If the shunt is of such a value that the meter is calibrated in milliamperes, the instrument is called a MILLIAMMETER. If the shunt is of such


SCALE CALIBRATED IN AMPS
TO REAR BALANCE SPRING
D'ARSONVAL MOVEMENT
N
S
FROM REAR BALANCE SPRING
METER LEADS
EXTERNAL SHUNT
VOLTAGE SOURCE FOR LOAD
LOAD

(A) INTERNAL CONSTRUCTION & CIRCUIT

(B) EXTERNAL VIEW


COPPER BLOCKS

(C) TYPICAL EXTERNAL AMMETER SHUNTS

Figure 12-5.—Weston ammeter employing D'Arsonval principle in its movement.

a value that the meter is calibrated in amperes, it is called an AMMETER.

A single type of standard meter movement is generally used in all ammeters, no matter what the range of a particular meter. For example, meters with working ranges of zero to 10 amperes, zero to 5 amperes, or zero to 1 ampere all use the same galvanometer movement. The designer of the ammeter simply calculates the correct shunt resistance required to extend the range of the one-milliampere meter movement to measure any desired amount of current. This shunt is then connected across the meter terminals. Shunts may be located inside the meter case (internal shunt) or somewhere away from the meter (external shunt), with leads going to the meter. An external shunt arrangement is shown in figure 12-5 (A). Some typical external shunts are shown in part (C).

The shunt strips are usually made of manganin; an alloy having an almost zero temperature coefficient of resistance. The ends of the shunt strips are embedded in heavy copper blocks to which are attached the meter coil leads and the line terminals. To insure accurate readings, the meter leads for a particular ammeter should not be used interchangeably with those for a meter of a different range. Slight changes in lead length and size may vary the resistance of the meter circuit and thus its current, and may cause an incorrect meter reading. External shunts are generally used where currents greater than 50 amperes must be measured.

It is important to select a suitable shunt when using an external shunt ammeter so that the scale indication is easily read. For example, if the scale has 150 divisions and the load current to be measured is known to be between 50 and 100 amperes, a 150-ampere shunt is suitable. If the scale deflection is 75 divisions, the load current is 75 amperes, the needle will deflect half-scale when using the same 150-ampere shunt.

A shunt having exactly the same current rating as the estimated normal load current should never be selected because any abnormally high load would drive the pointer off scale and might damage the movement. A good choice would bring the needle somewhere near the mid-scale indication, when the load is normal.

EXTENDING THE RANGE BY USE OF INTERNAL SHUNTS

For limited current ranges (below 50 amperes), internal shunts are most often employed. In this manner the range of the meter may be easily changed by selecting the correct internal shunt having the necessary current rating. Before the required resistance of the shunt for each range can be calculated, the resistance of the meter movement must be known.

For example, suppose it is desired to use a 100-microampere D'Arsonval meter having a resistance of 100 ohms to measure line currents up to 1 ampere. The meter deflects full scale when the current through the 100-ohm coil is 100 microamperes. Therefore, the voltage drop across the meter coil is *IR*, or

$$0.0001 \times 100 = 0.01 \text{ volt.}$$

Because the shunt and coil are in parallel, the shunt must also have a voltage drop of 0.01 volt. The current that flows through the shunt is the difference between the full-scale meter current and the line current. In this case, the meter current is 100×10^{-6}, or 0.0001 ampere. This current is negligible compared with the line (shunt) current, so the shunt current is approximately 1 ampere. The resistance, R_s, of the shunt is therefore

$$R_s = \frac{E}{I} = \frac{0.01}{1} = 0.01 \text{ ohm (approx.),}$$

and the range of the 100-microampere meter has been increased to 1 ampere by paralleling it with the 0.01-ohm shunt.

The 100-microampere instrument may also be converted to a 10-ampere meter by the use of a proper shunt. For full-scale deflection of the meter the voltage drop, E, across the shunt (and across the meter) is still 0.01 volt. The meter current is again considered negligible, and the shunt current is now approximately 10 amperes. The resistance, R_s, of the shunt is therefore

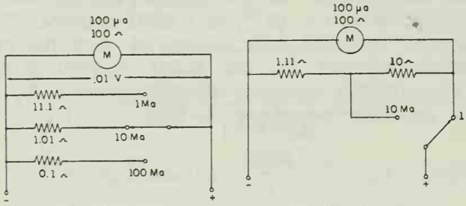
$$R_s = \frac{E}{I} = \frac{0.01}{10} = 0.01 \text{ ohm.}$$

The same instrument may likewise be converted to a 50-ampere meter by the use of the proper type of shunt. The current, I_S, through the shunt is approximately 50 amperes and the resistance, R_S, of the shunt is

$$R_s = \frac{E}{I_s} = \frac{0.01}{50} = 0.0002 \text{ ohm.}$$

Various values of shunt resistance may be used, by means of a suitable switching arrangement, to increase the number of current ranges that may be covered by the meter. Two switching arrangements are shown in figure 12-6. Figure 12-6 (A), is the simpler of the two arrangements from the point of view of calculating the value of the shunt resistors when a number of shunts are used. However, it has two disadvantages:

1. When the switch is moved from one shunt resistor to another the shunt is momentarily removed from the meter and the line current then flows through the meter coil. Even a momentary surge of current could easily damage the coil.
2. The contact resistance—that is, the resistance between the blades of the switch when they are in contact—is in series with the shunt but not with the meter coil. In shunts that must pass high currents the contact resistance becomes an appreciable part of the total shunt resistance. Because the contact resistance is of a variable nature, the ammeter indication may not be accurate.



SIMPLE ARRANGEMENT
(A)

PREFERRED ARRANGEMENT
(B)

Figure 12-6.—Ways of connecting internal shunts.

A more generally accepted method of range switching is shown in figure 12-6 (B). Although only two ranges are shown, as many ranges as needed can be used. In this type of circuit the range selector switch contact resistance is external to the shunt and meter in each range position, and therefore has no effect on the accuracy of the current measurement.

CURRENT-MEASURING INSTRUMENTS MUST ALWAYS BE CONNECTED IN SERIES WITH A CIRCUIT AND NEVER IN PARALLEL WITH IT. If an ammeter were connected across a constant-potential cource of appreciable voltage the shunt would become a short circuit, and the meter would burn out.

If the approximate value of current in a circuit is not known, it is best to start with the highest range of the ammeter and switch to progressively lower ranges until a suitable reading is obtained.

Most ammeter needles indicate the magnitude of the current by being deflected from left to right. If the meter is connected with reversed polarity, the needle will be deflected backwards, and this action may damage the movement. Hence the proper polarity should be observed in connecting the meter in the circuit. That is, the meter should always be connected so that the electron flow will be into the negative terminal and out of the positive terminal.

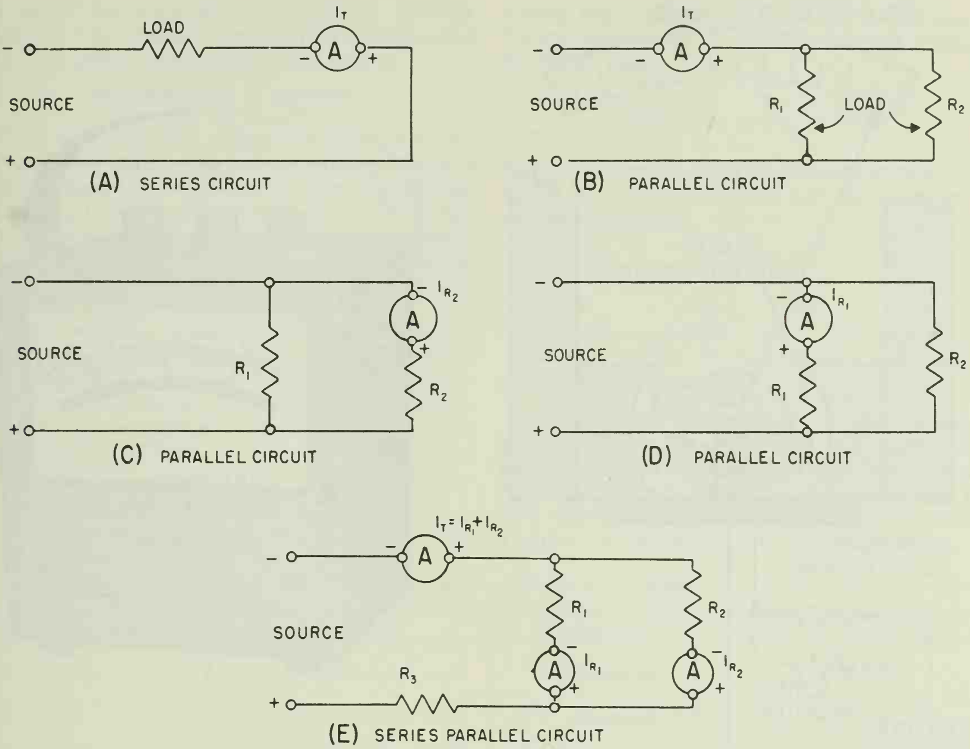
Figure 12-7 shows various circuit arrangements; the ammeter or ammeters are properly connected for measuring current in various portions of the circuits.

Voltmeter

CONSTRUCTION

The 100-microampere D'Arsonval meter used as the basic meter for the ammeter may also be used to measure voltage if a high resistance is placed in series with the moving coil of the meter. For low-range instruments, this resistance is mounted inside the case with the D'Arsonval movement and typically consists of resistance wire having a low temperature coefficient and wound either on spools or card frames. For higher voltage ranges, the series resistance may be connected externally. When this is done the unit containing the resistance is commonly called a MULTIPLIER.

A simplified diagram of a voltmeter is shown in figure 12-8 (A). The resistance coils are treated in such a way that a minimum amount of moisture will be absorbed by the insulation. Moisture reduces the insulation resistance and increases leakage currents, which cause incorrect readings. Leakage currents through the insulation increase with length of resistance wire and become a factor that limits the magnitude



LOAD
I_T
A
SOURCE
(A) SERIES CIRCUIT
I_T
A
SOURCE
R_1
LOAD
R_2
(B) PARALLEL CIRCUIT
SOURCE
R_1
A
I_{R_2}
R_2
(C) PARALLEL CIRCUIT
SOURCE
A
I_{R_1}
R_1
R_2
(D) PARALLEL CIRCUIT
$I_T = I_{R_1} + I_{R_2}$
A
SOURCE
R_1
R_2
R_3
I_{R_1}
I_{R_2}
(E) SERIES PARALLEL CIRCUIT

Figure 12-7.—Proper ammeter connections.

of voltage that may be measured. An external view of a voltmeter is shown in figure 12-8 (B).

EXTENDING THE RANGE

The value of the necessary series resistance is determined by the current required for full-scale deflection of the meter and by the range of voltage to be measured. Because the current through the meter circuit is directly proportional to the applied voltage, the meter scale can be calibrated directly in volts for a fixed series resistance.

For example, assume that the basic meter (microammeter) is to be made into a voltmeter with a full-scale reading of 1 volt. The coil resistance of the basic meter is 100 ohms, and 0.0001 ampere (100 microamperes) causes a full-scale deflection. The total resistance, *R*, of the meter coil and the series resistance is

$$R = \frac{E}{I} = \frac{1}{0.0001} = 10{,}000 \text{ ohms},$$

and the series resistance alone is

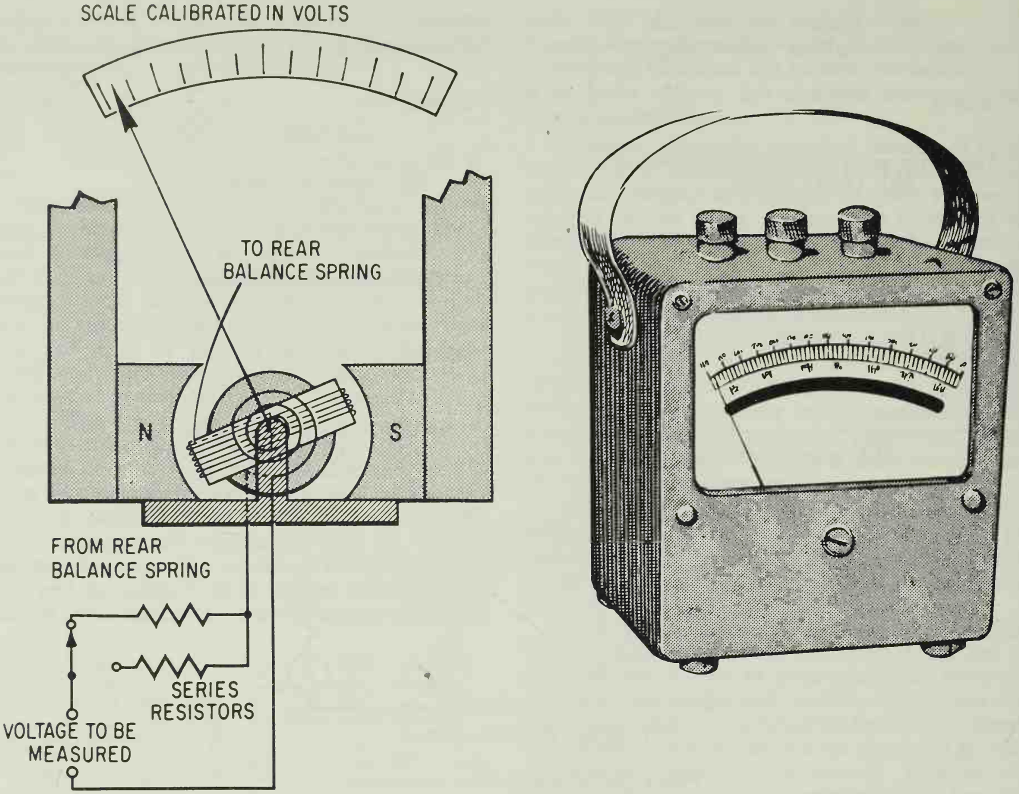
$$R_s = 10{,}000 - 100 = 9{,}900 \text{ ohms}.$$

Multirange voltmeters utilize one meter movement with the required resistances connected in series with the meter by a convenient switching arrangement. A multirange voltmeter with three ranges is shown in figure 12-9. The total circuit resistance for each of the three ranges beginning with the 1-volt range is:

$$R = \frac{E}{I} = \frac{1}{100} = 0.01 \text{ megohm},$$

$$= \frac{100}{100} = 1 \text{ megohm},$$

$$= \frac{1{,}000}{100} = 10 \text{ megohms}.$$


SCALE CALIBRATED IN VOLTS
TO REAR BALANCE SPRING
N
S
FROM REAR BALANCE SPRING
SERIES RESISTORS
VOLTAGE TO BE MEASURED

(A) INTERNAL CONSTRUCTION & CIRCUIT

(B) EXTERNAL VIEW

Figure 12-8.—Simplified voltmeter circuit.

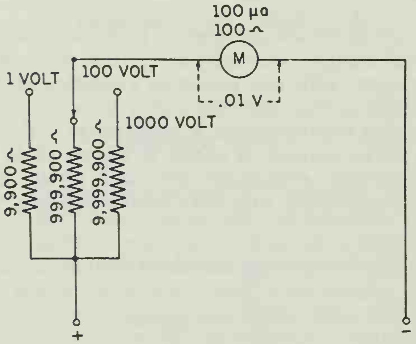

100 μa
100 Ω
M
1 VOLT
100 VOLT
1000 VOLT
.01 V
9,900 Ω
999,900 Ω
9,999,900 Ω
+
−

Figure 12-9.—Multirange voltmeter.

VOLTAGE-MEASURING INSTRUMENTS ARE CONNECTED ACROSS (IN PARALLEL WITH) A CIRCUIT. If the approximate value of the voltage to be measured is not known, it is best to start with the highest range of the voltmeter and progressively lower the range until a suitable reading is obtained.

In many cases, the voltmeter is not a central-zero indicating instrument. Thus, it is necessary to observe the proper polarity when connecting the instrument to the circuit, as is the case in connecting the d-c ammeter. The positive terminal of the voltmeter is always connected to the positive terminal of the source, and the negative terminal to the negative terminal of the source when the source voltage is being measured. In any case, the voltmeter is connected so that electrons will flow into the negative terminal and out of the positive terminal of the meter.

INFLUENCE IN A CIRCUIT

The function of a voltmeter is to indicate the potential difference between two points in a circuit. When the voltmeter is connected across a circuit, it shunts the circuit. If the voltmeter has low resistance it will draw an appreciable amount of current. The effective resistance of the circuit will be lowered and the voltage reading will consequently be lowered.

When voltage measurements are made in high-resistance circuits, it is necessary to use a high-resistance voltmeter to prevent the shunting action of the meter. The effect is less noticeable in low-resistance circuits because the shunting effect is less.

SENSITIVITY

The sensitivity of a voltmeter is given in ohms per volt, (Ω/E), and may be determined by dividing the resistance R_m, of the meter plus the series resistance, R_s, by the full-scale reading in volts. Thus,

$$\text{sensitivity} = \frac{R_m + R_s}{E}.$$

This is the same as saying that the sensitivity is equal to the reciprocal of the current (in amperes)—that is,

$$\text{sensitivity} = \frac{\text{ohms}}{\text{volts}} = \frac{1}{\frac{\text{volts}}{\text{ohms}}} = \frac{1}{\text{amperes}}.$$

Thus, the sensitivity of a 100-microampere movement is the reciprocal of 0.0001 ampere, or 10,000 ohms per volt.

Table 12-1 shows how the sensitivity of permanent-magnet movable-coil voltmeters has been increased over many years of manufacture. The table indicates the sensitivity of a 0 to 150-volt voltmeter, its resistance, and the current required to produce a full-scale deflection.

Table 12-1.—Increase in sensitivity in voltmeters.

Time of manufacture	Sensitivity	Resistance	Current to deflect full scale
Before 1924.	10 ohms per volt	1.5 k-ohms	100 ma.
After 1924.	100 ohms per volt	15 k-ohms	10 ma.
Today.	1,000 ohms per volt 20,000 ohms per volt 200,000 ohms per volt	150 k-ohms 3 megohms 30 megohms	1 ma. 50 μa. 5 μa.

The sensitivity has been increased by increasing the strength of the permanent magnet, by using lighter weight materials for the moving element (consistent with increased number of turns on the coil), and by using sapphire jewel bearings to support the moving coil.

ACCURACY

The accuracy of a meter is generally expressed in percent. For example, a meter that has an accuracy of 1 percent will indicate a value that is within 1 percent of the correct value. The statement means that if the correct value is 100 units, the meter indication may be anywhere within the range of 99 to 101 units.

Electrodynamometer-Type Meter

The electrodynamometer-type meter differs from the galvanometer-type meter in that no permanent magnet is used. Instead, two fixed coils are utilized to produce the magnetic field. Two movable coils are also used in this type meter.

The two fixed coils are connected in series and positioned coaxially, with a space between them. The two movable coils are also positioned coaxially, and are connected in series. The two pairs of coils (fixed pair and movable pair) are further connected in series with each other. The movable-coil unit is pivot-mounted between the fixed coils.

This meter arrangement is illustrated in figure 12-10.

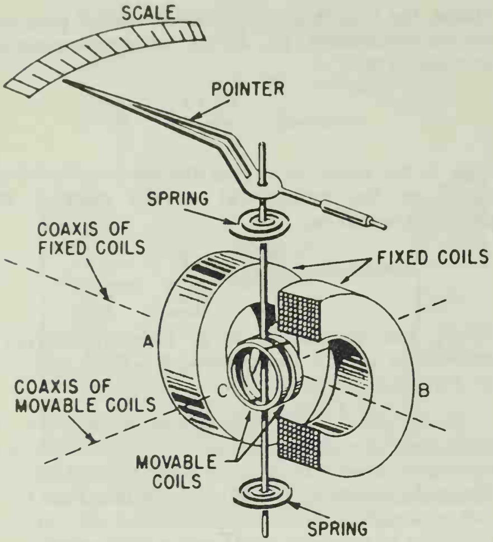


Figure 12-10.—Inside construction of an electrodynamometer.

The central shaft on which the movable coils are mounted is restrained by spiral springs which hold the pointer at zero when no current is flowing through the coil. These springs also serve as conductors for delivering current to the movable coils. Since these conducting springs are very small, the meter cannot carry a very heavy current.

When used as a voltmeter, no difficulty in construction is encountered, because the current required is not more than 0.1 ampere. This amount of current can be brought in and out of the moving coil through the springs. When the electrodynamometer is used as a voltmeter, its internal connections and construction are as shown in figure 12-11 (A). The fixed coils *a* and *b* are wound with fine wire, since the current through them will be no more than 0.1 ampere. They are connected directly in series with the movable coil *c* and the series current-limiter resistance. For ammeter applications, however, a special type construction must be used, because the large currents that flow through the meter cannot be carried through the moving coils.

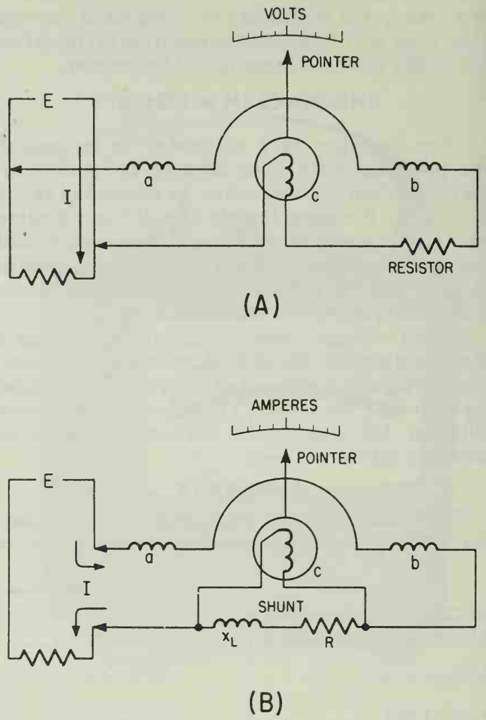


Figure 12-11.—Circuit arrangement of electrodynamometer type meter, (A) voltmeter, (B) ammeter.

In the ammeter, the stationary coils *a* and *b* of figure 12-11 (B), are generally wound of heavier wire, to carry up to five amperes. In parallel with the moving coils is an inductive shunt, which permits only a small part of the total current to flow through the moving coil. This current through the moving coil is directly proportional to the total current through the instrument. The shunt has the same ratio of reactance to resistance as has the moving coil, thus the instrument will be reasonably correct at all frequencies with which it is designed to be used.

The meter is mechanically damped by means of aluminum vanes that move in enclosed air chambers. Although electrodynamometer type meters are very accurate, they do not have the sensitivity of the D'Arsonval type meter. For this reason they are not widely used outside the laboratory.

Meter Used for Measuring Resistance

The two instruments most commonly used to check the continuity, or to measure the resistance of a circuit or circuit element, are the OHMMETER and the MEGGER (megohmmeter). The ohmmeter is widely used to measure resistance and check the continuity of electrical circuits and devices. Its range usually extends to only a few megohms. The megger is widely used for measuring insulation resistance, such as between a wire and the outer surface of its insulation, and insulation resistance of cables and insulators. The range of a megger may extend to more than 1,000 megohms.

OHMMETER

The ohmmeter consists of a d-c milliammeter, which was discussed earlier in this chapter, with a few added features. The added features are:

1. A d-c source of potential (usually a three-volt battery).
2. One or more resistors (one of which is variable). A simple ohmmeter circuit is shown in figure 12-12.

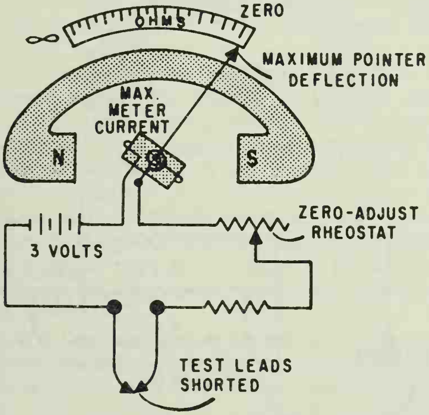


Figure 12-12.—Simple ohmmeter circuit.

The ohmmeter's pointer deflection is controlled by the amount of battery current passing through the moving coil. Before measuring the resistance of an unknown resistor or electrical circuit, the test leads of the ohmmeter are first shorted together, as shown in figure 12-12. With the leads shorted the meter is calibrated for proper operation on the selected range. (While the leads are shorted meter current is maximum and the pointer deflects a maximum amount, somewhere near the zero position on the ohms scale.) When the variable resistor (rheostat) is adjusted properly, with the leads shorted, the pointer of the meter will come to rest exactly on the zero graduation. This indicates ZERO RESISTANCE between the test leads, which in fact are shorted together. The zero readings of series-type ohmmeters are sometimes on the right-hand side of the scale, whereas the zero reading for ammeters and voltmeters is generally to the left-hand side of the scale. When the test leads of an ohmmeter are separated, the pointer of the meter will return to the left side of the scale, due to the interruption of current and the spring tension acting on the movable coil assembly.

After the ohmmeter is adjusted for zero reading, it is ready to be connected in a circuit to measure resistance. A typical circuit and ohmmeter arrangement is shown in figure 12-13.

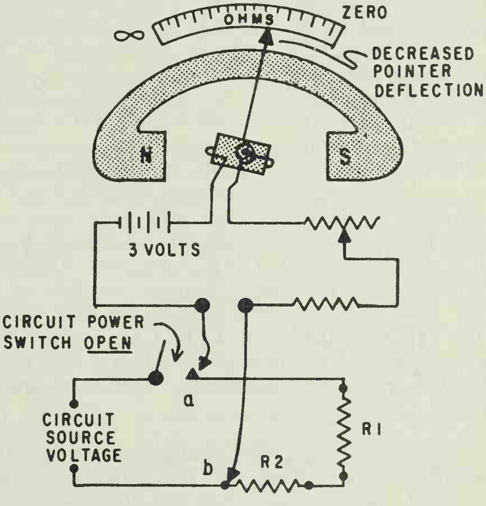


Figure 12-13.—Measuring circuit resistance with an ohmmeter.

The power switch of the circuit to be measured should always be in the OFF position. This prevents the circuit's source voltage from being applied across the meter, which could cause damage to the meter movement.

The test leads of the ohmmeter are connected across (in series with) the circuit to be measured. (See fig. 12-13.) This causes the current produced by the meter's three-volt battery to flow through the circuit being tested. Assume that the meter test leads are connected at points *a* and *b* of figure 12-13. The amount of current that flows through the meter coil will depend on the resistance of resistors, *R*1 and *R*2, plus the resistance of the meter. Since the meter has been preadjusted (zeroed), the amount of coil movement now depends solely on the resistance of *R*1 and *R*2. The inclusion of *R*1 and *R*2 raised the total series resistance, decreased the current, and thus decreased the pointer deflection. The pointer will now come to rest at a scale figure indicating the combined resistance of *R*1 and *R*2. If *R*1 or *R*2, or both, were replaced with a resistor(s) having a larger ohmic value, the current flow in the moving coil of the meter would be decreased still more. The deflection would also be further decreased, and the scale indication would read a still higher circuit resistance. Movement of the moving coil is proportional to the amount of current flow. The scale reading of the meter, in ohms, is inversely proportional to current flow in the moving coil.

The amount of circuit resistance to be measured may vary over a wide range. In some cases it may be only a few ohms, and in others it may be as great as 1,000,000 ohms. To enable the meter to indicate any value being measured, with the least error, scale multiplication features are incorporated in most ohmmeters. For example, a typical meter will have four test lead jacks, marked as follows—COMMON, *R* x 1, *R* x 10, and *R* x 100. The jack marked COMMON is connected internally through the battery to one side of the moving coil of the ohmmeter. The jacks marked *R* x 1, *R* x 10, and *R* x 100 are connected to three different size resistors located within the ohmmeter. This is shown in figure 12-14.

Some ohmmeters are equipped with a selector switch for selecting the multiplication scale desired, so that only two test lead jacks are necessary. Other meters have a separate jack for each range, as shown in figure 12-14. The range to be used in measuring any particular unknown resistance (R_x in fig. 12-14) depends on the approximate ohmic value of the unknown resistance. For instance, assume the ohmmeter scale in figure 12-14 is calibrated in divisions from zero to 1,000. If R_x is greater than 1,000 ohms, and the *R* x 1 range is being used, the ohmmeter cannot measure it. This occurs because the combined series resistance of resistor *R* x 1 and R_x is too great to allow sufficient battery current to flow to deflect the pointer away from infinity (∞). The test lead would have to be plugged into the next range, *R* x 10. With this done, assume the pointer deflects to indicate 375 ohms. This would indicate that R_x has 375 x 10 = 3,750 ohms resistance. The change of range caused the deflection because resistor *R* x 10 has only 1/10 the resistance of resistor *R* x 1. Thus, selecting the smaller series resistance permitted a battery current of sufficient amount to cause a useful pointer deflection. If the *R* x 100 range were used to measure the same 3,750-ohm resistor, the pointer would deflect still further, to the 37.5 ohm position. This increased deflection would occur because resistor *R* x 100 has only 1/10 the resistance of resistor *R* x 10.

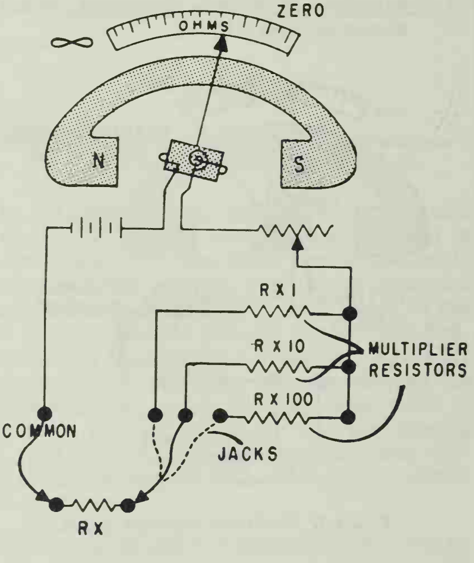


Figure 12-14.—Ohmmeter with multiplication jacks.

The foregoing circuit arrangement allows the same amount of current to flow through the meter's moving coil whether the meter measures 10,000 ohms on the *R* x 1 scale, or 100,000 ohms on the R x 10 scale, or 1,000,000 ohms on the R x 100 scale.

It always takes the same amount of current to deflect the pointer to a certain position on the scale (midscale position for example), regardless of the multiplication factor being used. Since the multiplier resistors are of different values, it is necessary to ALWAYS "zero" adjust the meter for each multiplication factor selected. The operator of the ohmmeter should select the multiplication factor that will result in the pointer coming to rest as near as possible to the midpoint of the scale. This enables the operator to read the resistance more accurately, because the scale readings are more easily interpreted at or near midpoint.

MEGGER

An ordinary ohmmeter cannot be used for measuring resistance of multimillions of ohms, such as conductor insulation. To adequately test for insulation breakdown, it is necessary to use a much higher potential than is furnished by an ohmmeter's battery. This potential is placed between the conductor and the outside surface of the insulation.

An instrument called a MEGGER (megohmmeter) is used for these tests. The megger (fig. 12-15 (A)) is a portable instrument consisting of two primary elements—(1) a hand-driven d-c generator, G, which supplies the necessary voltage for making the measurement, and (2) the instrument portion, which indicates the value of the resistance being measured. The instrument portion is of the opposed-coil type as shown in figure 12-15 (A). Coils a and b are mounted on the movable member c with a fixed angular relationship to each other, and are free to turn as a unit in a magnetic field. Coil b tends to move the pointer counterclockwise, and coil a clockwise.

Coil a is connected in series with $R3$ and the unknown resistance, R_x, to be measured. The combination of coil $R3$, and R_x form a direct series path between the + and - brushes of the d-c generator. Coil b is connected in series with $R2$ and this combination is also connected across the generator. There are no restraining springs on the movable member of the instrument portion of the megger. Therefore, when the generator is not operated, the pointer floats freely and may come to rest at any position on the scale.

The guard ring intercepts leakage current. Any leakage currents intercepted are shunted to the negative side of the generator. They do not flow through coil a; therefore, they do not affect the meter reading.

If the test leads are open-circuited, no current flows in coil a. However, current flows internally through coil b, and deflects the pointer to infinity, which indicates a resistance too large to measure. When a resistance such as R_x is connected between the test leads, current also flows in coil a, tending to move the pointer clockwise. At the same time, coil b still tends to move the pointer counterclockwise. Therefore, the moving element, composed of both coils and the pointer, comes to rest at a position at which the two forces are balanced. This position depends upon the value of the external resistance, which controls the relative magnitude of current in coil a. Because changes in voltage affect both coil a and coil b in the same proportion, the position of the moving system is independent of the voltage. If the test leads are short-circuited, the pointer rests at zero because the current in a is relatively large. The instrument is not injured under the circumstances because the current is limited by $R3$.

The external view of one type of megger is shown in figure 12-15 (B).

Meggers provided aboard ship usually are rated at 500 volts. To avoid excessive test voltages, most meggers are equipped with friction clutches. When the generator is cranked faster than its rated speed, the clutch slips and the generator speed and output voltage are not permitted to exceed their rated values. For extended ranges, a 1,000-volt generator is available. When extremely high resistances—for example, 10,000 megohms or more—are to be measured, a high voltage is needed to cause sufficient current flow to actuate the meter movement.

Multimeter

The MULTIMETER is a multipurpose instrument that can measure resistance, voltage, or current. It contains one milliammeter. The face of the instrument has separate graduated scales

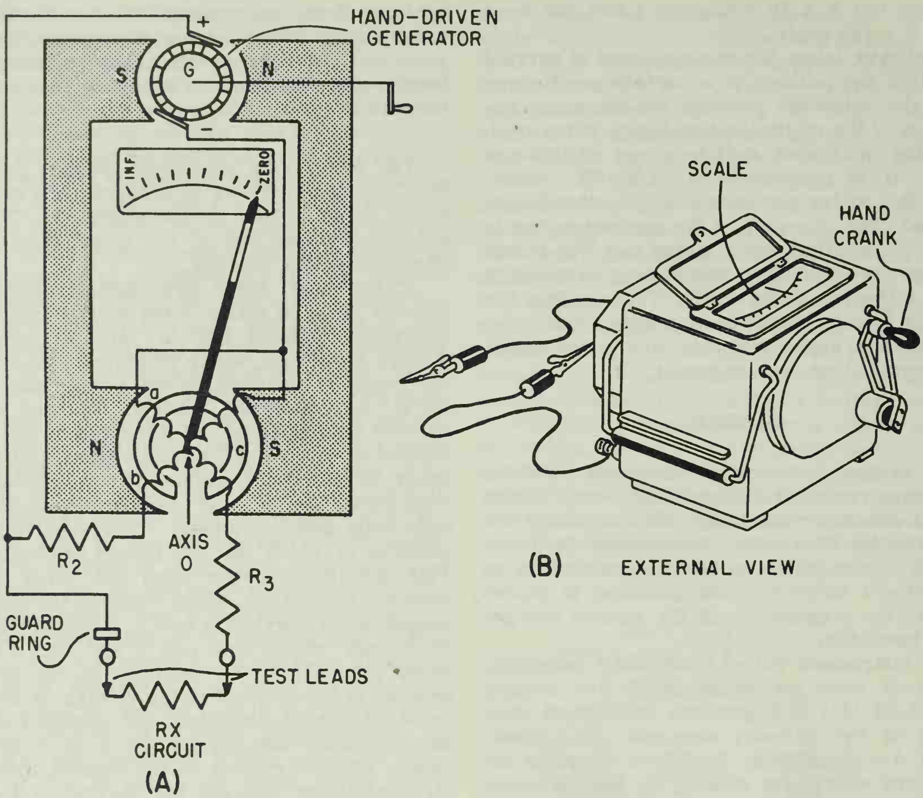


Figure 12-15.—(A) Megger internal circuit; (B) external view of megger.

to indicate the three values that can be measured. Figure 12-16 shows a multimeter that is widely used in the Navy today.

The front panel of the multimeter is constructed and labeled in such a way that all functions are self explanatory. One pin jack marked -DC ±AC OHMS is common to all functions and ranges. One test lead is always plugged into this common jack and the remaining lead into the jack marked for the particular function or range desired. The internal circuit arrangement of the meter is controlled by means of the FUNCTION switch. This switch selects the proper circuit elements for the type of measurement desired. The desired voltage, current or ohmmeter range is determined by the combined action of positioning the function and range switches and selecting certain pin jacks. The range switch selects the resistance or current range and the pin jacks select the voltage range. The function switch selects the type of operation to be performed. Separate pin jacks are provided for ohms and for the 10-ampere range. A CASE GROUND jack is connected directly to the cast aluminum case.

The meter panel contains the following operating controls:

1. FUNCTION SWITCH. This is a six position rotary switch which is clearly marked with the type of measurement to be taken. It is located in the lower left-hand corner of the front panel.

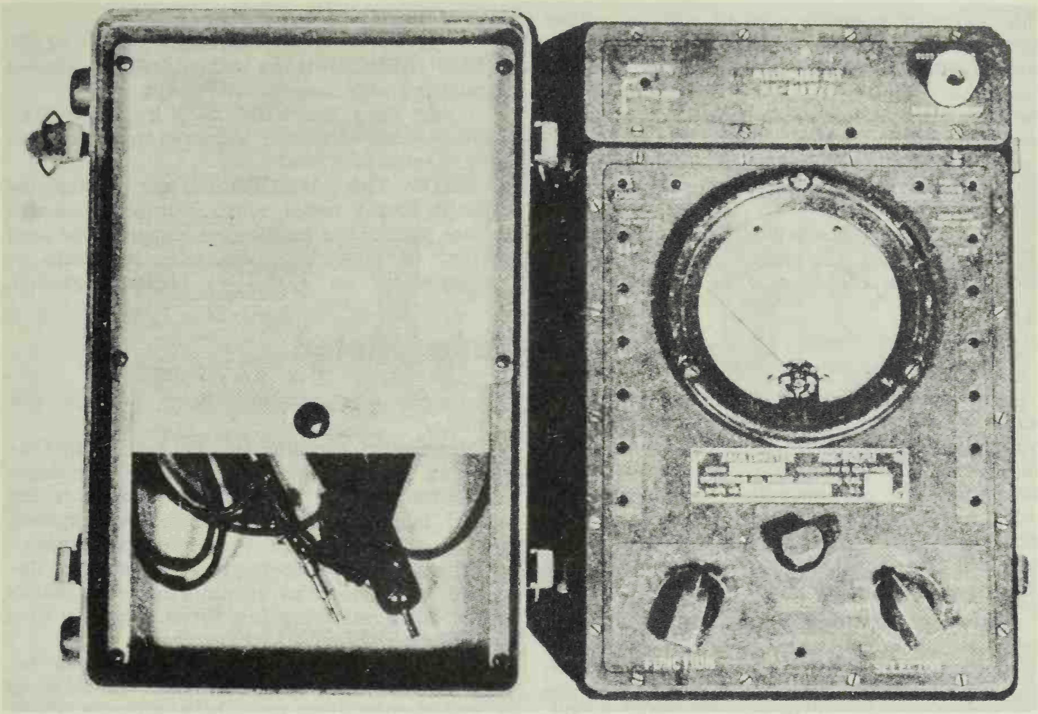


Figure 12-16.—Multimeter.

2. RANGE SWITCH. This is a twelve position switch used in selecting one of five resistance ranges or one of seven current ranges. This switch is located in the lower right-hand corner of the front panel. An additional current range (10 amperes) is brought out to a separate pin jack, because of the magnitude of the current.

3. OHMS ZERO ADJ. This control is a rheostat used to zero the pointer on the ohmmeter. With the test leads shorted the rheostat is turned until the pointer comes to rest at zero. The rheostat also serves to compensate for variations in battery voltage, and is located in the lower center section of the front panel.

The following operational procedures should be used when making measurements with the meter.

1. A-C VOLTS MEASUREMENTS. Turn FUNCTION switch to AC VOLTS. Plug one test lead into the ±AC jack. Plug the other lead into the desired 1,000 OHMS PER VOLT jack.

2. OHMS MEASUREMENTS. Turn FUNCTION switch to OHMS. Plug leads into the two OHMS jacks. Turn the range switch to the desired resistance range. Short the two test leads together and set the indicator pointer to zero ohms (top scale on the indicator) by rotating the OHMS ZERO ADJ.

3. D-C CURRENT MEASUREMENT. Turn FUNCTION switch to DC CURRENT. Plug the black test lead into the -DC jack. For ranges from 250 microamperes to 2.5 amperes full scale, plug the red lead into the jack marked +DC current. Use the jack marked +10 AMPS ONLY for current reading between 2.5 amperes and 10 amperes range.

4. D-C VOLTS MEASUREMENTS at 1,000 OHMS PER VOLT. Turn the FUNCTION switch to 1,000 Ω/VDC. Plug the black lead into the -DC jack. Plug the red lead into the desired range jack.

5. D-C VOLTS MEASUREMENTS at 20,000 OHMS PER VOLT. An indicator reversing position is available on the 20,000 ohms per volt measurements and is selected by indexing the FUNCTION switch to DIRECT or REVERSE.

This permits measurement of voltage, either positive or negative in polarity, while still keeping the instrument case and the common d-c input jack at the same potential as the chassis of the device under check. Accordingly, the following procedure should always be followed when using the 20,000 ohms per volt ranges, particularly where the 1,000 or 5,000 volt ranges are used.

a. Plug the black lead into the -DC jack.

b. Connect the other end of the black lead solidly to the chassis or exposed metal part of the device under check.

c. Turn the FUNCTION switch to "20,000 Ω/VDC DIRECT" if the voltage to be measured is positive with respect to chassis.

d. Turn the FUNCTION switch to REVERSE if the voltage is expected to be negative with respect to chassis.

NOTE: The CASE GROUND jack is connected directly to the metal case. It is not connected to any part of the multimeter circuit. For protection of operating personnel it should be jumpered to an earth or common ground.

Moving Iron-Vane Meter

The moving iron-vane meter is another basic type of meter. Unlike the D'Arsonval-type meter, which employs permanent magnets, the moving iron-vane meter depends on induced magnetism for its operation. It employs the principle of repulsion between two concentric iron vanes, one fixed and one movable, placed inside a coil, as shown in figure 12-17 (A). A pointer is attached to the movable vane.

When current flows through the coil, the two iron vanes become magnetized with north poles at their upper ends and south poles at their lower ends for one direction of current through the coil, as shown in the figure. Because like poles repel, the unbalanced component of force tangent to the movable element causes it to turn against the force exerted by the springs.

The movable vane is rectangular in shape, and the fixed vane is tapered. This design permits the use of a relatively uniform scale.

When no current flows through the coil, the movable vane is positioned so that it is opposite the larger portion of the tapered fixed vane, and the scale reading is zero. The amount of magnetization of the vanes depends on the strength of the field, which in turn, depends on the amount of current flowing through the coil. The force of repulsion is greater opposite the larger end of the fixed vane than it is nearer the smaller end. Therefore, the movable vane moves toward the smaller end through an angle that is proportional to the magnitude of the coil current. The movement ceases when the force of repulsion is balanced by the restoring force of the spring.

Because the repulsion is always in the same direction (toward the smaller end of the fixed vane) regardless of the direction of current flow through the coil, the moving iron-vane instrument operates on either d-c or a-c circuits.

Mechanical damping in this type of instrument is obtained by the use of an aluminum vane attacked to the shaft (not shown in the figure) in such a way that, as the shaft moves, the vane moves in a restricted air space.

When the moving iron-vane meter is designed to be used as an ammeter, the coil is wound with relatively few turns of large wire in order to carry the rated current.

When the moving iron-vane meter is designed to be used as a voltmeter the solenoid is wound with many turns of small wire. Portable voltmeters are made with self-contained series resistance for ranges up to 750 volts. Higher ranges are obtained by the use of additional external multipliers. An external view of a moving iron-vane meter is shown in figure 12-17 (B).

The moving iron-vane instrument may be used to measure direct current, but has an error due to residual magnetism in the vanes. The error may be minimized by reversing the meter connections and averaging the readings. When used on a-c circuits the instrument has an accuracy of 0.5 percent. Because of its simplicity, its relatively low cost, and the fact that no current is conducted to the moving element, this type of movement is used extensively to measure current and voltage in a-c power circuits.

However, because the reluctance of the magnetic circuit is high, the moving iron-vane meter requires much more power to produce full-scale deflection than is required by a D'Arsonval meter of the same range. Therefore, the moving iron-vane meter is seldom used in high-resistance low-power circuits.

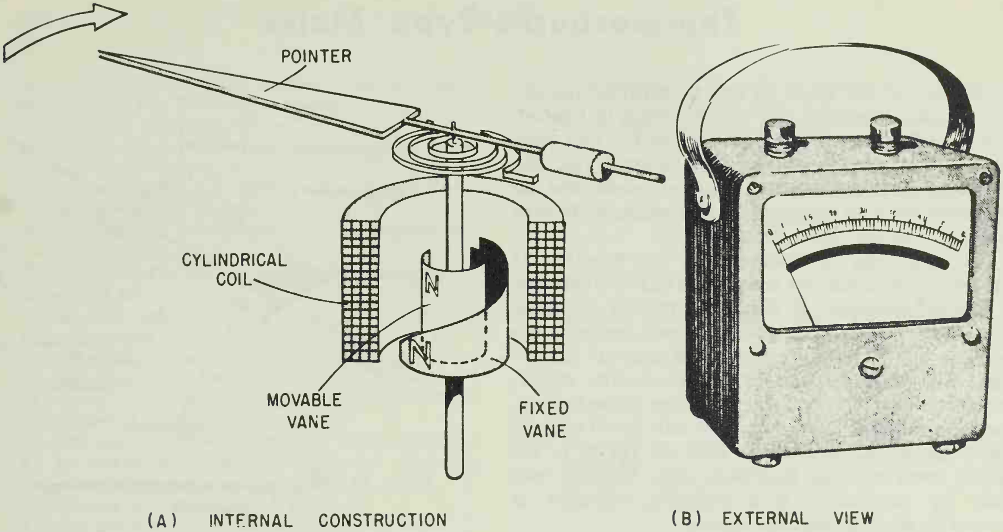


Figure 12-17.—(A) Simplified diagram of a moving iron-vane meter, (B) external view.

Inclined-Coil Iron-Vane Meter

The principle of the moving iron-vane mechanism is applied to the inclined-coil type of meter shown in figure 12-18. The inclined-coil iron-vane meter has a coil mounted at an angle to the shaft. Attached obliquely to the shaft, and located inside the coil, are two soft-iron vanes. When no current flows through the coil, a control spring holds the pointer at zero and the iron vanes lie in planes parallel to the plane of the coil. When current flows through the coil, the vanes tend to line up with magnetic lines passing through the center of the coil at right angles to the plane of the coil. Thus the vanes rotate against the spring action to move the pointer over the scale.

The iron vanes tend to line up with the magnetic lines regardless of the direction of current flow through the coil. Therefore, the inclined-coil iron-vane meter can be used to measure either alternating current or direct current. The aluminum disk and the drag magnets provide electromagnetic damping.

Like the moving iron-vane meter, the inclined-coil type requires a relatively large amount of current for full-scale deflection and hence is seldom used in high-resistance low-power circuits.

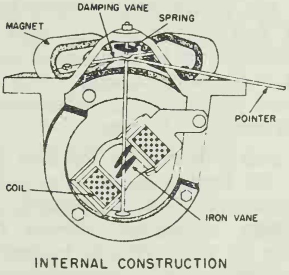


Figure 12-18.—Inclined-coil iron-vane meter.

As in the moving iron-vane instrument, the inclined-coil instrument is wound with few turns of relatively large wire when used as an ammeter and with many turns of small wire when used as a voltmeter.

Thermocouple-Type Meter

If two of the ends of two dissimilar metals are welded together and this junction is heated, a d-c voltage is developed across the two open ends. The voltage developed depends on the material of which the wires are made and on the difference in temperature between the heated junction and the open ends.

In one type of instrument, the junction is heated electrically by the flow of current through a heater element. It does not matter whether the current is alternating or direct because the heating effect is independent of current direction. The maximum current that may be measured depends on the current rating of the heater, the heat that the thermocouple can stand without being damaged, and on the current rating of the meter used with the thermocouple. Voltage may also be measured if a suitable resistor is placed in series with the heater.

A simplified schematic diagram of one type of thermocouple is shown in figure 12-19. The input current flows through the heater strip via the terminal blocks. The function of the heater strip is to heat the thermocouple, which is composed of a junction of two dissimilar wires welded to the heater strip. The open ends of these wires are connected to the center of two copper compensating strips. The function of these strips is to radiate heat so that the open ends of the wires will be much cooler than the junction end of the wires; thus permitting a higher voltage to be developed across the open ends of the thermocouple. The compensating strips are thermally and electrically insulated from the terminal blocks.

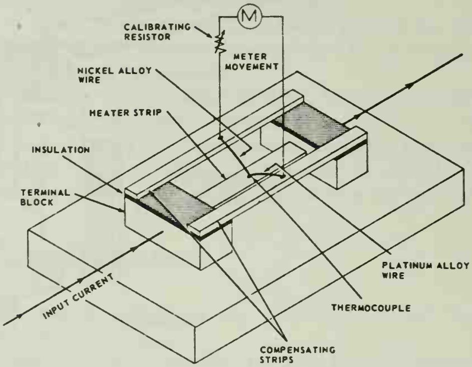


Figure 12-19.—Simplified schematic of one type of thermocouple.

The heat produced by the flow of line current through the heater strip is proportional to the square of the heating current ($P = I^2R$). Because the voltage appearing across the two open terminals is proportional to the temperature, the movement of the meter element connected across these terminals is proportional to the square of the current flowing through the heater element. The scale of the meter is crowded near the zero end, and is progressively less crowded near the maximum end of the scale. Because the lower portion of the scale is crowded the reading is necessarily less accurate. For the sake of accuracy in making a given measurement, it is desirable to choose a meter in which the deflection will extend at least to the more open portion of the scale.

The meter used with the thermocouple should have low resistance to match the low resistance of the thermocouple, and it must deflect full scale when rated current flows through the heater. Because the resistance must be low and the sensitivity high, the moving element must be light.

A more nearly uniform meter scale may be obtained if the permanent magnet of the meter is constructed so that as the coil rotates (needle moves up scale), it moves into a magnetic field of less and less density. The torque then increases approximately as the first power of the current instead of as the square of the current, and a more linear scale is achieved.

If the thermocouple is burned out by excessive current through the heater strip, it may be replaced and the meter recalibrated by means of the calibrating variable resistor.

QUIZ

1. In a D'Arsonval type meter, the primary purpose of the iron core is to
   a. dampen coil movement
   b. concentrate the flux between the core and the pole piece
   c. concentrate the flux between the core and the hairsprings
   d. weaken the flux between the core and the pole piece
2. The D'Arsonval movement operates on the principle of
   a. mutual induction
   b. repulsion
   c. magnetic repulsion and attraction
   d. magnetic attraction
3. In order to measure large currents with the D'Arsonval ammeter,
   a. the meter must be made more rugged
   b. an increased number of turns must be put on the moving coil
   c. shunts are used
   d. the pointer must be lengthened
4. The primary purpose of the megger is to measure
   a. milliohms
   b. kilohms
   c. megohms
   d. microhms
5. A moving iron-vane meter works on the principle of
   a. induction
   b. repulsion
   c. conduction
   d. attraction
6. When hairsprings are used in a D'Arsonval type meter, they
   a. serve as conductors
   b. are wound oppositely and provide restoring forces
   c. are attached to the ends of the bobbin
   d. all of the above are true
7. The metal ribbons attached to the moving coil in the galvanometer have no force on them when the
   a. north pole of the moving coil is close to the south pole of the horseshoe magnet
   b. north pole of the moving coil is as close as possible to the north pole of the horseshoe magnet
   c. north pole of the moving coil is 90° from the north pole of the horseshoe magnet
   d. none of the above
8. When shunts are used with an ammeter they
   a. must be located within the case
   b. must be located outside the case
   c. may be located either inside or outside the case
   d. reduce the accuracy of the movement
9. The power supply for a megger comes from
   a. two flashlight batteries
   b. a hand-driven generator
   c. any 115 v. wall plug
   d. the aircraft battery
10. The iron-vane meter can be used on
    a. a.c. only
    b. a.c. and d.c.
    c. d.c. only
    d. rectified a.c.
11. The Weston meter uses the principle of operation of the
    a. D'Arsonval galvanometer
    b. Thompson incline coil
    c. iron vane
    d. V. T. V. M.
12. Current-measuring instruments must always be connected in
    a. parallel with a circuit
    b. series with a circuit
    c. series-parallel with a circuit
    d. delta with the shunt
13. If the pointer fails to come back to zero when the megger is not in use,
    a. the megger is out of calibration
    b. this is normal operation
    c. the hairsprings are burned out
    d. the pointer is stuck
14. When using ammeters,
    a. reverse polarity must be used
    b. + or - polarity can be used
    c. polarity should be observed
    d. regardless of polarity, the instrument cannot be damaged because it is grounded
15. For measuring resistances of multimillions of ohms, use a/an
    a. TS 297 multimeter
    b. ohmmeter with high scales
    c. megger
    d. combustion volt ammeter
16. Dampening is accomplished in the iron-vane meter by
    a. hairsprings
    b. the hermetically sealed case
    c. an aluminum bobbin
    d. an aluminum vane
17. Balance springs on each end of the shaft of the Weston ammeter
    a. are used to carry current to the moving coil
    b. are not balanced due to temperature change
    c. provide a turning force for the pointer
    d. are factory adjusted and must not be readjusted

18. The electrodynamometer-type meter employs
    a. two permanent magnets
    b. one permanent magnet and one electromagnet
    c. two fixed coils and one movable permanent magnet
    d. none of the above

19. With the ohmmeter setting on R x 1, it takes 0.01 ma. to deflect the pointer to half scale. If the meter was set on R x 100, how much would it take to deflect the pointer to half scale?
    a. 0.1 ma.
    b. 0.01 ma.
    c. 0.001 ma.
    d. 1.0 ma.

20. Electrodynamometer-type meters
    a. never utilize shunts
    b. utilize four coils, all of which are movable
    c. are seldom used in the laboratory because they are not accurate enough
    d. are not as sensitive as the D'Arsonval meter

21. Meggers provided aboard ships are usually rated at
    a. 250 volts
    b. 500 volts
    c. 750 volts
    d. 1,000 volts

22. The voltage developed in the thermocouple-type meter depends on the
    a. material of which the wires are made
    b. direction of current flow
    c. frequency of the heater voltage
    d. the type of meter movement

23. A multimeter contains a
    a. voltmeter and wattmeter
    b. voltmeter and frequency meter
    c. voltmeter, ohmmeter, and milliammeter
    d. voltmeter, ammeter, and ohmmeter

PART 2

CHAPTER 13

GENERATORS AND TRANSFORMERS ALTERNATING-CURRENT

A-C Generators

Most of the electric power for use aboard ship and ashore is generated by alternating-current generators. A-c generators are also finding increased use in aircraft, and even automobiles.

A-c generators are made in many different sizes, depending on their intended use. For example, any one of the generators at Boulder Dam can produce millions of volt-amperes, while generators used on aircraft produce only a few thousand volt-amperes.

Regardless of size, however, all generators operate on the same basic principle—a magnetic field cutting through conductors, or conductors passing through a magnetic field. Thus, all generators will have at least two distinct sets of conductors. They are (1) a group of conductors in which the output voltage is generated, and (2) a second group of conductors through which DIRECT CURRENT is passed to obtain an electromagnetic field of fixed direction. The conductors in which the output voltage is generated are always referred to as the ARMATURE WINDINGS. The conductors in which the electromagnetic field originates are always referred to as the FIELD WINDINGS.

In addition to the armature and field, there must also be MOTION between the two. To provide this, a-c generators are built in two major assemblies, the STATOR and the ROTOR. The rotor rotates inside the stator. It may be driven by any one of a number of commonly used power sources, such as gas or hydraulic turbines, electric motors, and steam or internal-combustion engines.

TYPES OF A-C GENERATORS

Revolving Armature

In the revolving-armature a-c generator, the stator provides a stationary electromagnetic field. The rotor, acting as the armature, revolves in the field, cutting the lines of force, producing the desired output voltage. In this generator, the armature output is taken through sliprings and thus retains its alternating characteristic.

For a number of reasons, the revolving-armature a-c generator is seldom used. Its primary limitation is the fact that its output power is conducted through sliding contacts (sliprings and brushes). These contacts are subject to frictional wear and sparking. In addition, they are exposed, and thus liable to arc-over at high voltages. Consequently, revolving-armature generators are limited to low-power low-voltage applications.

Revolving Field

The revolving-field a-c generator (fig. 13-1) is by far the most widely used type. In this type of generator, direct current from a separate source is passed through windings on the rotor by means of sliprings and brushes. This maintains a rotating electromagnetic field of fixed polarity (similar to a rotating bar magnet). The rotating magnetic field, following the rotor, extends outward and cuts through the armature windings imbedded in the surrounding stator. As the rotor turns, alternating voltages are induced in the windings since magnetic fields of first one polarity and then the other cut through them. Since the output power is taken from stationary windings, the output may be connected through fixed terminals directly to the external loads, as through terminals *T1* and *T2* in figure 13-1. This is advantageous, in that there are no sliding contacts, and the whole output circuit is continuously insulated, thus minimizing the danger of arc-over.

Sliprings and brushes are still used on the rotor to supply d.c. to the field; they are adequate for this purpose, because the power level in the field is much lower than in the armature circuit.

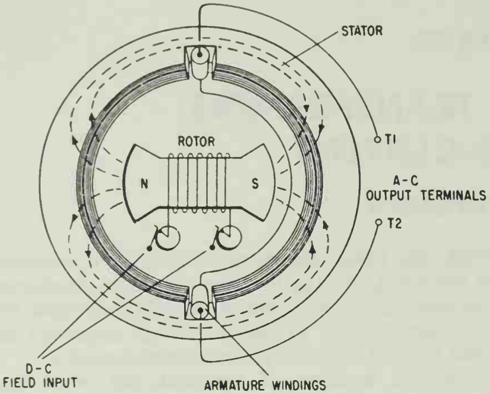

STATOR
ROTOR
N
S
T1
A-C
OUTPUT TERMINALS
T2
D-C
FIELD INPUT
ARMATURE WINDINGS

Figure 13-1.—Essential parts of rotating-field a-c generator.

RATING OF A-C GENERATORS

The RATING of an a-c generator pertains to the load it is capable of supplying. The normal-load rating is the load it can carry continuously. Its overload rating is the above-normal load which it can carry for specified lengths of time only. The load rating of a particular generator is determined by the internal heat it can withstand. Since heating is caused mainly by current flow, the generator's rating is identified very closely with its CURRENT capacity.

The maximum current that can be supplied by an a-c generator depends upon (1) the maximum heating loss (I^2R power loss) that can be sustained in the armature and (2) the maximum heating loss that can be sustained in the field. The armature current varies with the load. This action is similar to that of d-c generators. In a-c generators, however, lagging power-factor loads tend to demagnetize the field, and terminal voltage is maintained only by increasing the d-c field current. Therefore, a-c generators are rated in terms of armature load current and voltage output, or kilovolt-ampere (kv.-a.) output, at a specified frequency and power factor. The specified power factor is usually 80 percent lagging. For example, a single-phase a-c generator designed to deliver 100 amperes at 1,000 volts is rated at 100 kv.-a. This machine would supply a 100-kw. load at unity power factor or an 80-kw. load at 80 percent power factor. If, however, the a-c generator supplied a 100 kv.a. load at 20 percent power factor, the required increase in d-c field current needed to maintain the desired terminal voltage would cause excessive heating in the field.

Basic Functions of Generator Parts

Almost all rotating-field a-c generators used in the Navy are actually two generators in one. A typical machine consists of the a-c generator and a smaller d-c generator built in a single unit. The output of the a-c generator section supplies alternating current to the load for which the generator was designed. The d-c generator's only purpose is to supply the direct current required to maintain the a-c generator field. This d-c generator is referred to as the EXCITER. A typical a-c generator is shown in figure 13-2 (A); figure 13-2 (B) is a simplified schematic of the generator.

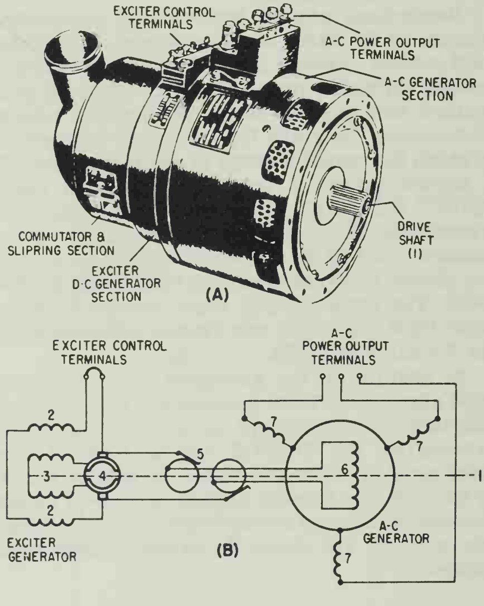

EXCITER CONTROL
TERMINALS
A-C POWER OUTPUT
TERMINALS
A-C GENERATOR
SECTION
COMMUTATOR &
SLIPRING SECTION
EXCITER
D-C GENERATOR
SECTION
DRIVE
SHAFT
(1)
(A)
EXCITER CONTROL
TERMINALS
A-C
POWER OUTPUT
TERMINALS
2
3
4
5
6
7
7
1
2
EXCITER
GENERATOR
(B)
A-C
GENERATOR
7

Figure 13-2.—A-c generator and schematic.

Any rotary generator requires a prime moving force (1, fig. 13-2) to rotate the a-c field and exciter armature. This rotary force is transmitted to the generator through the rotor drive shaft and is usually furnished by a combustion engine, turbine, or electric motor. The **EXCITER SHUNT FIELD** (2) creates an area of intense magnetic flux between its poles. When the **EXCITER ARMATURE** (3) is rotated in the exciter field flux, voltage is induced into the exciter armature windings. The **EXCITER OUTPUT COMMUTATOR** and **BRUSHES** (4) connects the exciter output directly to the **A-C GENERATOR FIELD INPUT SLIPRINGS** and **BRUSHES** (5). Since these sliprings, rather than a commutator, are used to supply current through the **A-C GENERATOR FIELD** (6), current will always flow in one direction only through these windings. Thus, a **FIXED POLARITY** magnetic field is maintained at all times in the a-c generator field windings. When the a-c generator field is rotated, its magnetic flux is passed through and across the **A-C GENERATOR ARMATURE WINDINGS** (7). Remember, a voltage is induced into a conductor if it is stationary and a magnetic field is passed across the conductor, the same as if the field is stationary and the conductor is moved. The alternating voltage induced in the a-c generator armature windings is connected through fixed terminals to the a-c load.

Construction

A-c generators used in the Navy are divided into three classes according to the type of prime mover—(1) low-speed engine-driven, (2) high-speed turbine-driven, and (3) aircraft engine-driven high-speed, 4,000 and 8,000 r.p.m.

The stator, or armature, of the revolving-field a-c generator is built up from steel punchings, or laminations. The laminations of an a-c generator stator form a steel ring that is keyed or bolted to the inside circumference of a steel frame. The inner surface of the laminated ring has slots in which the stator winding is placed.

The low-speed engine-driven a-c generator (fig. 13-3) has a large diameter revolving field with many poles, and a stationary armature relatively short in axial length. The stator (fig. 13-3 (A)) contains the armature windings, and the rotor (fig. 13-3 (B)) consists of salient poles, on which are mounted the d-c field windings. The exciter armature is the smaller unit shown in the foreground and mounted on an extension of the a-c generator shaft.

The high-speed turbine-driven a-c generator (fig. 13-4) is connected either directly or through gears to a steam turbine. The enclosed metal structure is a part of a forced ventilation system that carries away the heat by circulation of the air through the stator (fig. 13-4 (A)) and rotor (fig. 13-4 (B)). The exciter is a separate unit (not shown). The enclosed stator directs the paths of the circulating air-cooling currents and also reduces windage noise.

The aircraft a-c generator (fig. 13-5) may be driven directly by the aircraft engine, a hydraulic constant-speed drive, or an air turbine.

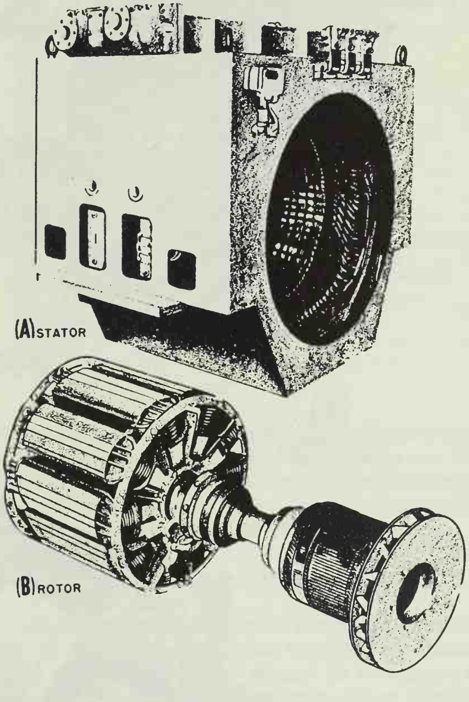


Figure 13-3.—Low-speed engine-driven a-c generator.

SINGLE-PHASE GENERATORS

A single-phase a-c generator has a stator made up of a number of windings in series, which form a single circuit in which an output voltage is generated. The principle of the single-phase a-c generator is described first, and the polyphase a-c generator is described later.

Figure 13-6 illustrates a schematic diagram of a single-phase a-c generator having four poles. The stator has four polar groups evenly

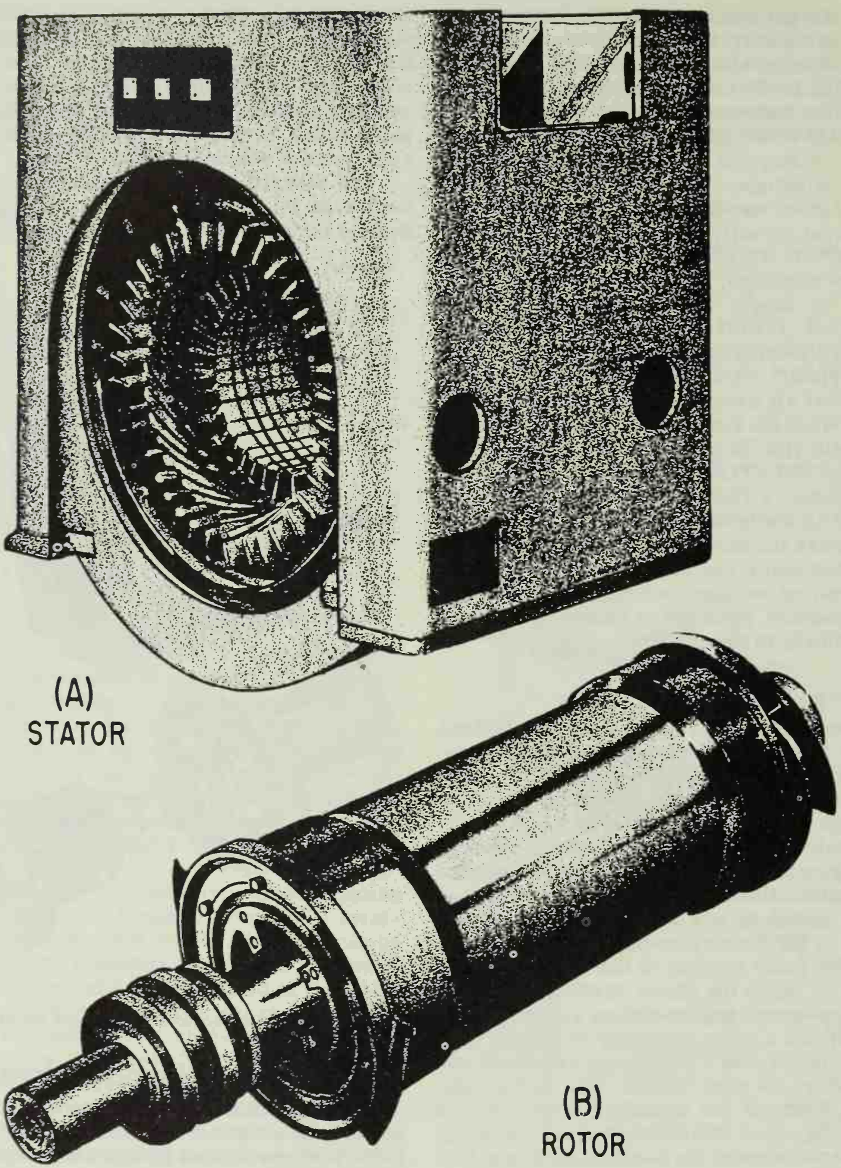

(A)
STATOR
(B)
ROTOR

Figure 13-4.—High-speed turbine-driven a-c generator.

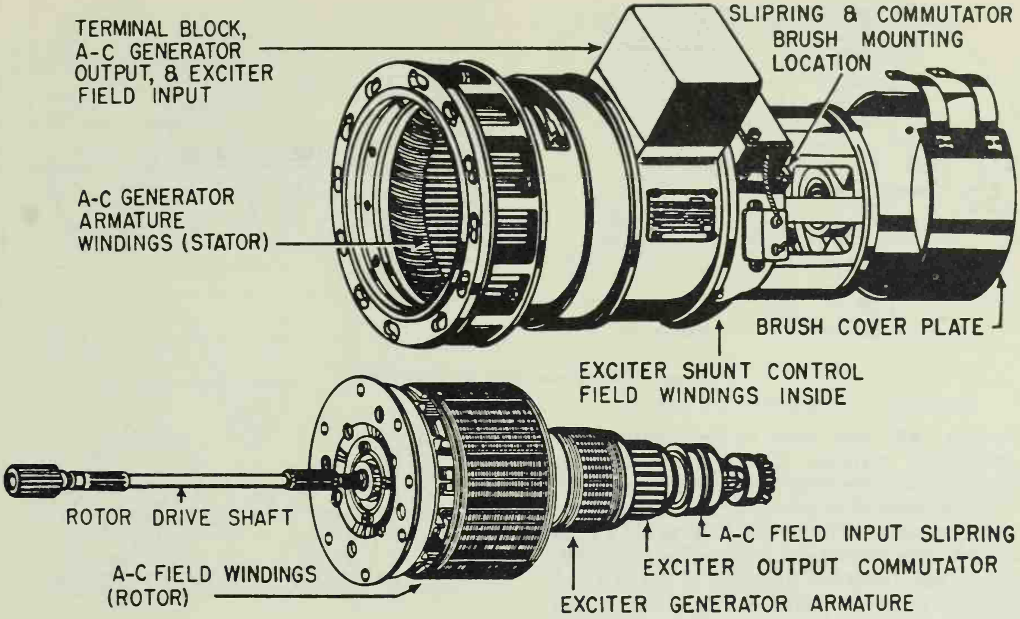

TERMINAL BLOCK, A-C GENERATOR OUTPUT, & EXCITER FIELD INPUT
SLIPRING & COMMUTATOR BRUSH MOUNTING LOCATION
A-C GENERATOR ARMATURE WINDINGS (STATOR)
BRUSH COVER PLATE
EXCITER SHUNT CONTROL FIELD WINDINGS INSIDE
ROTOR DRIVE SHAFT
A-C FIELD INPUT SLIPRING
EXCITER OUTPUT COMMUTATOR
A-C FIELD WINDINGS (ROTOR)
EXCITER GENERATOR ARMATURE

Figure 13-5.—Aircraft a-c generator.

spaced around the stator frame. The rotor has four poles, with adjacent poles of opposite polarity. As the rotor revolves, a-c voltages are induced in the stator windings. Since one rotor pole is in the same position relative to a stator winding as any other rotor pole, all stator polar groups are cut by equal amounts of magnetic lines of force at any given time. As a result, the voltages induced in all the windings have the same amplitude, or value, at any given instant. The four stator windings are connected to each other so that the a-c voltages are in phase, or "series aiding." Assume that rotor pole 1, a south pole, induces a voltage in the direction indicated by the arrow in stator winding 1. Since rotor pole 2 is a north pole, it will induce a voltage in the opposite direction in stator coil 2 with respect to that in coil 1.

In order that the two induced voltages be in series addition, the two coils are connected as shown. Applying the same reasoning, the voltage induced in stator coil 3 (clockwise rotation of the field) is in the same direction (counterclockwise) as the voltage induced in coil 1. Similarly, the direction of the voltage induced in winding 4 is opposite to the direction of the voltage induced in coil 1. All four stator coil groups are connected in series so that the voltages induced in each winding add to give a total voltage that is four times the voltage in any one winding.

TWO-PHASE GENERATORS

Multiphase or polyphase a-c generators have two or more single-phase windings symmetrically spaced around the stator. In a 2-phase a-c generator there are two single-phase windings physically spaced so that the a-c voltage induced in one is 90° out of phase with the voltage induced in the other. The windings are electrically separate from each other. When one winding is being cut by maximum flux, the other is being cut by no flux. This condition establishes the 90° relation between the two phases.

Figure 13-7 is a schematic diagram of a 2-phase 4-pole a-c generator. The stator consists of two single-phase windings (phases) completely separated from each other. Each phase is made up of four windings, which are connected in series so that their voltages add. The rotor

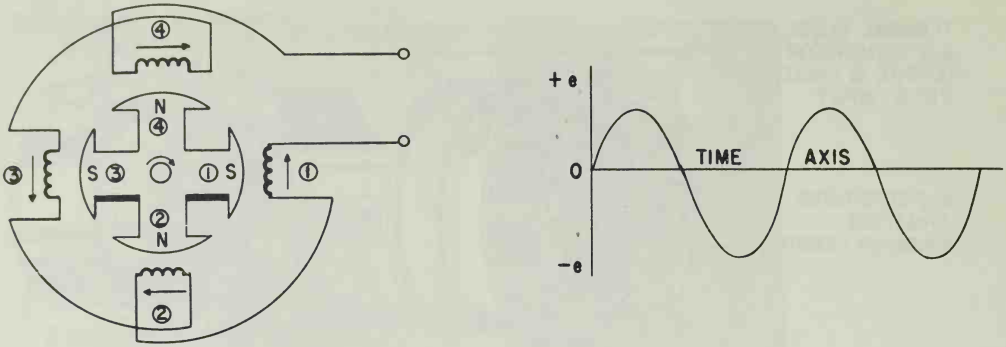
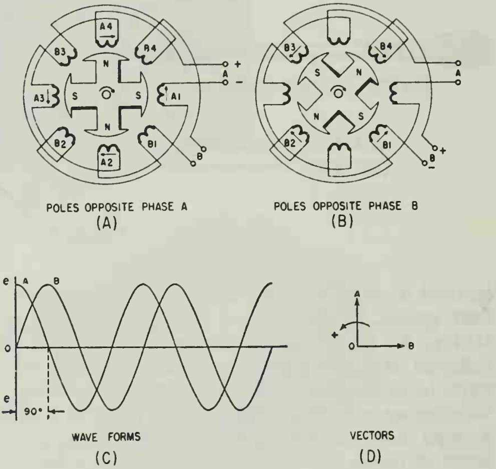


Figure 13-6.—Single-phase a-c generator.

is identical with that used in the single-phase a-c generator. In figure 13-7 (A), the rotor poles are opposite all of the coils of phase *A*. Therefore, the voltage induced in phase *A* is maximum and the voltage induced in phase *B* is zero. As the rotor continues rotating in a clockwise direction, it moves away from the windings of phase *A* and approaches those of phase *B*. As a result, the voltage in phase *A* decreases from its maximum value and the voltage in phase *B* increased from zero. In figure 13-7 (B), the rotor poles are opposite the windings of phase *B*. Now the voltage induced in phase *B* is maximum; whereas the voltage induced in phase *A* has dropped to zero. Notice that in the 4-pole a-c generator a 45° mechanical rotation of the rotor corresponds electrically to one quarter cycle, or 90 electrical degrees. Figure 13-7 (C) illustrates the waveforms of the voltage generated in each of the two phases. Both are sine curves, and *A* leads *B* by 90°. Figure 13-7 (D) illustrates the vectors representing the 2-phase voltages. Vector *A* leads vector *B* by 90°.



POLES OPPOSITE PHASE A (A)

POLES OPPOSITE PHASE B (B)

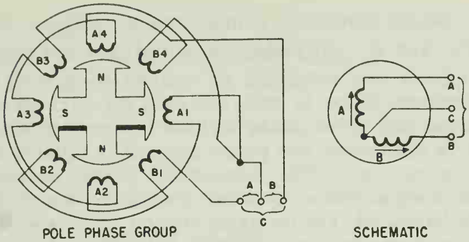
WAVE FORMS (C)

VECTORS (D)

Figure 13-7.—Two-phase four-pole a-c generator.

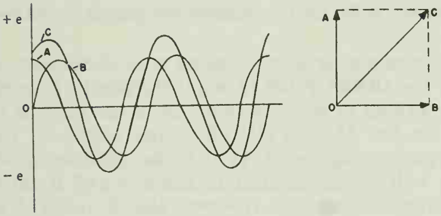
The two phases of a 2-phase a-c generator can be connected to each other as shown in figure 13-8, so that only three leads are brought out to the load. The a-c generator is then called a 2-phase 3-wire a-c generator. The two phases for a 4-pole a-c generator are shown in figure 13-8 (A). A simplified schematic diagram is shown in figure 13-8 (B), in which the rotor is omitted and each phase is indicated as a single coil. The two coils are drawn at right angles to each other to represent the 90° phase displacement between their respective voltages. The three wires make possible three different load connections—*(A)* and *(B)* across phases *A* and *B*, respectively, and *(C)* across both phases in series. The third voltage *(C)* is displaced 45° from the *A* and *B* phase voltages and is their vector sum. If each phase voltage has an effective value of 100 volts, the vector sum of these voltages will be the hypotenuse of a right triangle, the base and altitude of which are each 100 volts. This hypotenuse is equal to

$$\frac{100}{\cos 45^\circ}, \text{ or } \frac{100}{0.707}\ 141 \text{ volts.}$$



POLE PHASE GROUP
(A)

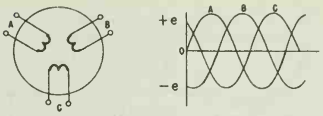
SCHEMATIC
(B)



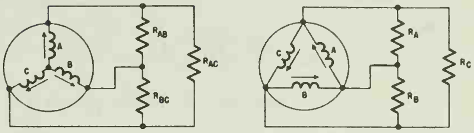
WAVE FORMS
(C)

VECTORS
(D)

Figure 13-8. Two-phase three-wire a-c generator.



SIMPLIFIED SCHEMATIC AND WAVE FORMS
(A)



WYE CONNECTION
(B)

DELTA CONNECTION
(C)

Figure 13-9.—Three-phase a-c generator.

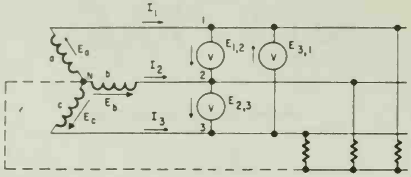
THREE-PHASE GENERATORS

The 3-phase a-c generator, as the name implies, has three single-phase windings spaced so that the voltage induced in each winding is 120° out of phase with the voltages in the other two windings. A schematic diagram of a 3-phase stator showing all the coils becomes complex, and it is difficult to see what is actually happening. A simplified schematic diagram, showing all the windings of a single phase lumped together as one winding, is illustrated in figure 13-9 (A). The rotor is omitted for simplicity. The waveforms of voltage are shown to the right of the schematic. The three voltages are 120° apart and are similar to the voltages that would be generated by three single-phase a-c generators whose voltages are out of phase by angles of 120°. The three phases are independent of each other.

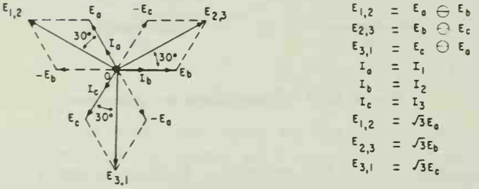
The Wye Connection

Rather than have six leads come out of the 3-phase a-c generator, one of the leads from each phase may be connected to form a common junction. The stator is then called WYE, or STAR, connected. The common lead may or may not be brought out of the machine. If it is brought out, it is called the NEUTRAL. The simplified schematic (fig. 13-9(B)) shows a wye-connected stator with the common lead not brought out. Each load is connected across two phases in series. Thus, R_{ab} is connected across phases *A* and *B* in series, R_{ac} is connected across phases *A* and *C* in series, and R_{bc} is connected across phases *B* and *C* in series. Thus, the voltage across each load is larger than the voltage across a single phase. In a wye-connected a-c generator the three start ends of each single-phase winding are connected together to a common neutral point and the opposite, or finish, ends are connected to the line terminals *A*, *B*, and *C*. These letters are always used to designate the three phases of a 3-phase system, or the three line wires to which the a-c generator phases connect. A 3-phase wye-connected a-c generator supplying three separate loads is shown in figure 13-10 (A). When unbalanced loads are used, a neutral may be added as shown in the figure by the broken line between the common neutral point and the loads. The neutral wire serves as a common return circuit for all three phases and maintains a voltage balance across the loads. No current flows in the neutral wire when the loads are balanced. This system is a 3-phase 4-wire circuit and is used to distribute 3-phase power to shore-based installations. The 3-phase 4-wire system is not used aboard ship, but is widely used in industry and for aircraft a-c power systems.

The phase relations in a 3-wire 3-phase wye-connected system are shown in figure 13-10 (B). In constructing vector diagrams of 3-phase



CIRCUIT
(A)



VECTORS
(B)

Figure 13-10.—Three-phase wye-connected system.

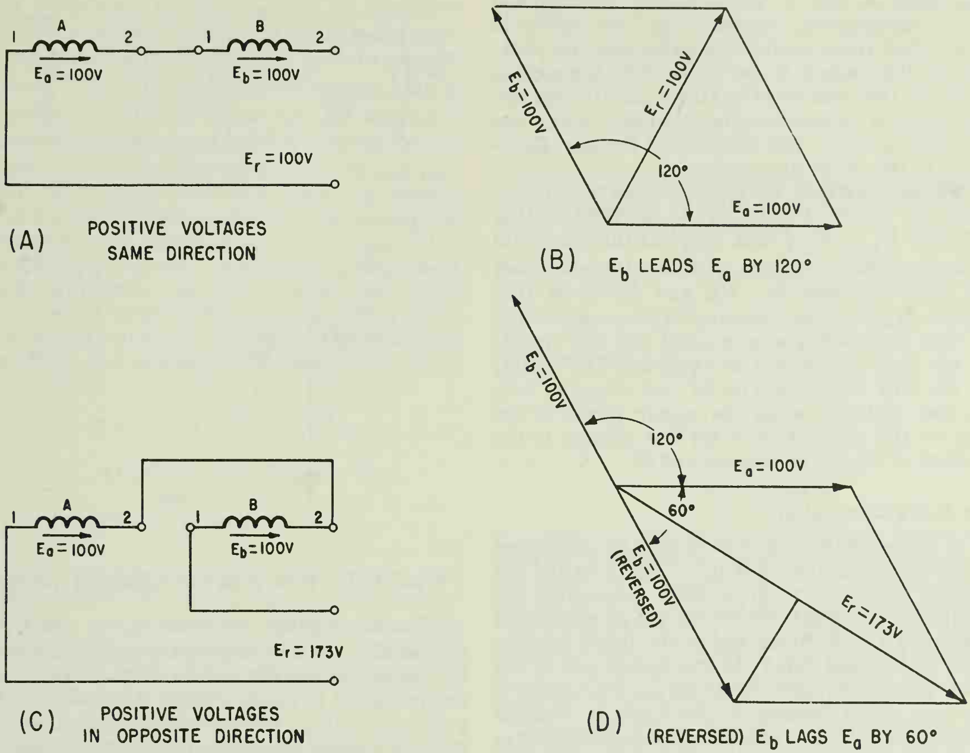
circuits, a counterclockwise rotation is assumed in order to maintain the correct phase relation between line voltages and currents. Thus, the a-c generator is assumed to rotate in such a direction as to generate the three phase voltages in the order, E_a, E_b, E_c.

The voltage in phase *b*, or E_b, lags the voltage in phase *a*, or E_a, by 120°. Likewise, E_c lags E_b by 120°, and E_a lags E_c by 120°. In figure 13-10 (A), the arrows E_a, E_b, and E_c, represent the positive direction of generated voltage in the wye-connected a-c generator. The arrows I_1, I_2, and I_3 represent the positive direction of phase and line currents supplied to balanced unity power-factor loads connected in wye. The three voltmeters connected between lines 1-2, 2-3, and 3-1, respectively, indicate effective values of line voltage. The line voltage is greater than the voltage of a phase in the wye-connected circuit because there are two phases connected in series between each pair of line wires, and their voltages combine. Line voltage is not twice the value of phase voltage, however, because the phase voltages are not in phase with each other.

The relation between phase and line voltages is shown in the vector diagram. Effective values of phase voltage are indicated by vectors, E_a, E_b, and E_c. Effective values of line and phase current are indicated by vectors I_a, I_b, and I_c. Because there is only one path for current between any given phase and the line wire to which it is connected, the phase current is equal to the line current. The respective phase currents have equal values because the load is assumed to be balanced. For the same reason, the respective line currents have equal values. When the load has unity power factor, the phase currents are in phase with their respective phase voltages.

In combining a-c voltages it is necessary to know the DIRECTION in which the positive maximum values of the voltages act in the circuit as well as the MAGNITUDES of the voltages. For example, in figure 13-11 (A), the positive maximum voltage generated in coils *A* and *B* act in the direction of the arrows, and *B* leads *A* by 120°. This arrangement may be obtained by assuming coils *A* and *B* to be two armature windings located 120° apart. If each voltage has an effective value of 100 volts, the total voltage is $E_r = 100$ volts, as shown by the polar vectors in figure 13-11 (B).

If the connections of coil *B* are reversed (fig. 13-11 (C)) with respect to their original connections, the two voltages will be in opposition, as will be seen by tracing around the circuit in the direction of the arrow in coil *A*. The positive direction of the voltage in coil *B* is opposite to the direction of the trace; the positive direction of the voltage generated in coil *A* is the same as that of the trace; hence, the two voltages are in opposition. This effect is the same as though the positive maximum value of E_b were 60° out of phase with that of E_a, and E_b acted in the same direction as E_a when the circuit trace was made (fig. 13-11 (D)) to vector E_a is accomplished by reversing the position of E_b from that shown in figure 13-11 (B) to the position shown in figure 13-11 (D) and completing the parallelogram. If E_a and E_b are each 100 volts, $E_r = \sqrt{3} \times 100$, or 173 volts. The value of E_r may be derived in the following manner: Erecting a perpendicular to E_r divides the isosceles triangle into two equal right triangles each having a hypotenuse of 100 volts and a base of 100 cos 30°, or 86.6 volts. The total length of E_r is 2 x 86.6, or 173.2 volts.



(A) POSITIVE VOLTAGES SAME DIRECTION

(B) E_b LEADS E_a BY 120°

(C) POSITIVE VOLTAGES IN OPPOSITE DIRECTION

(D) (REVERSED) E_b LAGS E_a BY 60°

Figure 13-11.–Vector analysis of voltages in series aiding and opposing.

To construct the line voltage vectors $E_{1,2}$, $E_{2,3}$, and $E_{3,1}$, in figure 13-10, it is first necessary to trace a path around the closed circuit which includes the line wires, armature windings, and one of the three voltmeters. For example, in figure 13-10 (A), consider the circuit that includes the upper and middle wires, the voltmeter connected across them, and the a-c generator phases *a* and *b*. The circuit trace is started at the center of the wye, proceeds through phase *a* of the a-c generator, out line 1, down through the voltmeter from line 1 to line 2, and through phase *b* of the a-c generator back to the starting point. Voltage drops along line wires are disregarded. The voltmeter indicates an effective value equal to the vector sum of the effective value of voltage in phases *a* and *b*. This value is the line voltage, $E_{1,2}$. According to Kirchhoff's law, the source voltage between lines 1 and 2 equals the voltage drop across the voltmeter connected to these lines.

If the direction of the path traced through the GENERATOR is the SAME as that of the arrow, the sign of the voltage is PLUS; if the direction of the trace is OPPOSITE to the arrow, the sign of the voltage is MINUS. If the direction of the path traced through the VOLTMETER is the SAME as that of the arrow, the sign of the voltage is MINUS; if the direction of the trace is OPPOSITE to that of the arrow, the sign of the voltage is PLUS.

The following equations for voltage are based on the preceding rules:

$$E_a \oplus (-E_b) = E_{1,2}, \text{ or } E_{1,2} = E_a \ominus E_b.$$

$$E_b \oplus (-E_c) = E_{2,3}, \text{ or } E_{2,3} = E_b \ominus E_c.$$

$$E_c \oplus (-E_a) = E_{3,1}, \text{ or } E_{3,1} = E_c \ominus E_a.$$

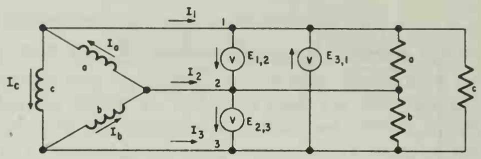
The signs ⊕ and ⊖ mean vector addition and vector subtraction, respectively. One vector is subtracted from another by reversing the position of the vector to be subtracted through an angle of 180° and constructing a parallelogram, the sides of which are the reversed vector and the other vector. The diagonal of the parallelogram is the difference vector.

These equations are applied to the vector diagram of figure 13-10 (B), to derive the line voltages $E_{1,2}$, $E_{2,3}$, and $E_{3,1}$, as the diagonals of three parallelograms of which the sides are the phase voltages E_a, E_b, and E_c. From this vector diagram, the following facts are observed: (1) The line voltages are equal and 120° apart; (2) the line currents are equal and 120° apart; (3) the line currents are 30° out of phase with the line voltages when the power factor of the load is 100 percent; and (4) line voltage is the product of the phase voltage and $\sqrt{3}$.

The Delta Connection

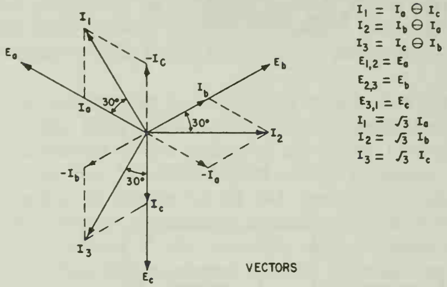
A three-phase stator may also be connected as shown in figure 13-9 (C). This is called the DELTA connection. In a delta-connected a-c generator, the start end of one phase winding is connected to the finish end of the third; and the start end of the third, to the finish end of the first. The three junction points are connected to the line wires leading to the load. A 3-phase delta-connected a-c generator is represented at the left (fig. 13-12 (A)). The generator is connected to a 3-phase 3-wire circuit which supplies a 3-phase delta-connected load at the right-hand end of the 3-phase line. Because the phases are connected directly across the line wires, phase voltage is equal to line voltage. When the generator phases are properly connected in delta, no appreciable current flows within the delta loop when there is no external load connected to the generator. If any one of the phases is reversed with respect to its correct connection, a short-circuit current will flow within the windings on no load, causing damage to the windings.

To avoid connecting a phase in reverse it is necessary to test the circuit before closing the delta. This may be done by connecting a voltmeter or fuse wire between the two ends of the delta loop before closing the delta. The two ends of the delta loop should never be connected if there is an indication of any appreciable current or voltage between them when no load is connected to the generator.



CIRCUIT

(A)



VECTORS

(B)

Figure 13-12.—Three-phase delta-connected system.

The three phase currents, I_a, I_b, and I_c, are indicated by accompanying arrows in the generator phases at the left in figure 13-12 (A). These arrows point in the direction of the positive current and voltage of each phase. The three voltmeters connected across lines 1-2, 2-3, and 3-1, respectively, indicate effective values of line and phase voltage. Line current I_1 is supplied by phases *a* and *c*, which are connected to line 1. Line current is greater than phase current, but not twice as great because the phase currents are not in phase with each other. The relation between line currents and phase currents is shown in figure 13-12 (B).

Effective values of line and phase voltages are indicated by vectors E_a, E_b, and E_c. Note that the vector sum of E_a, E_b, and E_c is zero. The phase currents are equal to each other because the loads are balanced. The line currents are equal to each other for the same reason. At unity-power-factor loads, the phase current and phase voltage have a 0° angle between them.

To construct the line current vectors it is first necessary to consider the direction of currents at the junctions of the line wires and the generator phases. Consider the junction formed by phase *a*, phase *c*, and line 1. According to Kirchhoff's law, line current I_1 is equal to the vector difference between I_a and I_c. In figure 13-12 (B), current vector I_a is in the same general direction as current vector I_1 (less than 90° displaced from I_1), and current vector I_c is in opposition to vector I_1 (more than 90° displaced from it). I_1 is the vector sum of I_a and $-I_c$. These are two equal values of phase current and they are 60° out of phase with each other. The vector sum of all the currents entering and leaving the junction is zero. Current arrows that point toward the junction are considered to represent positive currents. Current arrows that point away from the junction are considered to represent negative currents. The following equations for current are based on the preceding rules:

$$I_a \oplus (-I_c) = I_1, \text{ or } I_1 = I_a \ominus I_c.$$

$$I_b \oplus (-I_a) = I_2, \text{ or } I_2 = I_b \ominus I_a.$$

$$I_c \oplus (-I_b) = I_3, \text{ or } I_3 = I_c \ominus I_b.$$

Here also, the signs $\oplus$ and θ mean vector addition and vector subtraction, respectively. Vector subtraction is accomplished again by reversing the vector being subtracted through an angle of 180° and combining it with the other vector by the parallelogram method to form the diagonal which is the vector difference.

If the current equations are applied to the vector diagram of figure 13-12 (B), the line current I_1, I_2, and I_3 are derived as diagonals of the three parallelograms in which the sides are the phase currents I_a, I_b, and I_c. From this diagram the following facts are observed: (1) The line currents are equal and 120° apart; (2) the line voltages are equal and 120° apart; (3) the line currents are 30° out of phase with the line voltages when the power factor of the load is unity; and (4) the line current is equal to the product of the phase current and $\sqrt{3}$.

The power delivered by a balanced 3-phase wye-connected system is equal to three times the power delivered by each phase. The total true power is

$$P_t = 3E_{\text{phase}} I_{\text{phase}} \cos\theta$$

Because $E_{\text{phase}} = \dfrac{E_{\text{line}}}{\sqrt{3}}$ and $I_{\text{phase}} = I_{\text{line}}$,

the total true power is

$$P_t = 3\frac{E_{\text{line}}}{\sqrt{3}} I_{\text{line}} \cos\theta,$$

$$= \sqrt{3}\, E_{\text{line}} I_{\text{line}} \cos\theta.$$

The power delivered by a balanced 3-phase delta-connected system is also three times the power delivered by each phase.

Because $E_{\text{phase}} = E_{\text{line}}$ and $I_{\text{phase}} = \dfrac{I_{\text{line}}}{\sqrt{3}}$

the total true power is

$$P_t = 3E_{\text{line}} \frac{I_{\text{line}}}{\sqrt{3}} \cos\theta,$$

$$= \sqrt{3} E_{\text{line}} I_{\text{line}} \cos\theta.$$

Thus, the expression for 3-phase power delivered by a balanced delta-connected system is the same as the expression for 3-phase power delivered by a balanced wye-connected system. Two examples are given to illustrate the phase relations between current, voltage, and power in (1) a 3-phase wye-connected system and (2) a 3-phase delta-connected system.

Example 1: A 3-phase wye-connected a-c generator has a terminal voltage of 450 volts and delivers a full-load current of 300 amperes per terminal at a power factor of 80 percent. Find (a) the phase voltage, (b) the full-load current per phase, (c) the kilovolt-ampere, or apparent power, rating, and (d) the true power output.

(a) $E_{\text{phase}} = \dfrac{E_{\text{line}}}{\sqrt{3}} = \dfrac{450}{\sqrt{3}} = 260$ volts.

(b) $I_{\text{phase}} = I_{\text{line}} = 300$ amperes.

(c) Apparent power $= \sqrt{3}\, E_{\text{line}} I_{\text{line}}$

$= \sqrt{3} \times 450 \times 300 = 233{,}600$ va., or 233.6 kv.-a.

(d) True power $= \sqrt{3}\, E_{\text{line}} I_{\text{line}} \cos\theta$

$= \sqrt{3} \times 450 \times 300 \times 0.8$

$=$ 186,000 watts, or 186.8 kw.

Example 2: A 3-phase delta-connected a-c generator has a terminal voltage of 450 volts and the current in each phase is 200 amperes. The power factor of the load is 75 percent. Find (a) the line voltage, (b) the line current, (c) the apparent power, and (d) the true power.

(a) $E_{phase} = E_{line} = 450$ volts.

(b) $I_{line} = \sqrt{3}\, I_{phase} = 1.732 \times 200 = 346$ amperes.

(c) Apparent power $= \sqrt{3}\, E_{line} I_{line}$
$= 1.732 \times 450 \times 346 = 269{,}000$ va., or 269 kv.-a.

(d) True power $= \sqrt{3}\, E_{line} I_{line} \cos \theta$

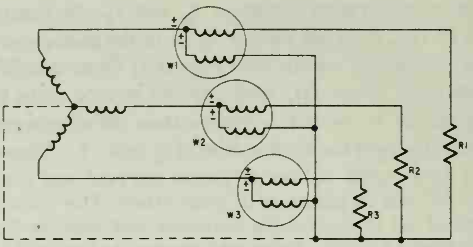
$= 1.732 \times 450 \times 346 \times 0.75$

$= 201{,}700$ watts, or 201.7 kw.

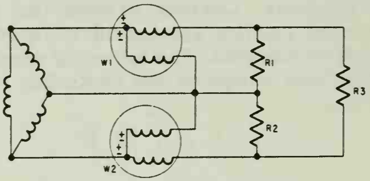
MEASUREMENT OF POWER

The wattmeter connections for measuring the true power in a 3-phase system are shown in figure 13-13. The method shown in figure 13-13 (A) uses three wattmeters with their current coils inserted in series with the line wires and their potential coils connected between line and neutral wires. The total true power is equal to the arithmetic sum of the three wattmeter readings.

The method shown in figure 13-13 (B) uses two wattmeters with their current coils connected in series with two line wires and their potential coils connected between these line wires and the common, or third, wire that does not contain the current coils. The total true power is equal to the algebraic sum of the two wattmeter readings. If one meter reads backward, its potential coil connections are first reversed to make the meter read up-scale and the total true power is then equal to the difference in the two wattmeter readings. If the load power factor is less than 0.5 and the loads are balanced, the total true power will be equal to the difference in the two wattmeter readings. If the load power factor is 0.5, one meter will indicate the total true power and the other will indicate zero. If the load power factor is above 0.5, the total true power is equal to the sum of the two wattmeter readings.



THREE-WATTMETER METHOD
(A)



TWO-WATTMETER METHOD
(B)

Figure 13-13.—Wattmeter connection for measurement of power in a 3-phase system.

FREQUENCY

The frequency of the a-c generator voltage depends upon the speed of rotation of the rotor and the number of poles. The faster the speed, the higher the frequency will be; and the lower the speed, the lower the frequency becomes. The more poles there are on the rotor, the higher the frequency will be for a given speed. When a rotor has rotated through an angle such that two adjacent rotor poles (a north and a south pole) have passed one winding, the voltage induced in that winding will have varied through one complete cycle. For a given frequency, the more pairs of poles there are, the lower will be the speed of rotation. A 2-pole generator rotates at twice the speed of a 4-pole generator for the same frequency of generated voltage. The frequency of the generator in cycles per second is related to the number of poles and the speed, as expressed by the equation

$$f = \frac{P}{2} \times \frac{N}{60} = \frac{PN}{120}$$

where P is the number of poles and N the speed in r.p.m. For example, a 2-pole 3,600 r.p.m. generator has a frequency of $\frac{2 \times 3{,}600}{120} = 60$

cycles per second; a 4-pole 1,800-r.p.m. generator has the same frequency; and a 6-pole 500-r.p.m. generator has a frequency of $\frac{6 \times 500}{120} = 25$ cycles per second, and a 12-pole 4,000 r.p.m. generator has a frequency of $\frac{12 \times 4{,}000}{120} = 400$ cycles per second.

GENERATED VOLTAGE

Once the machine has been designed and built, the generated voltage of an a-c generator is controlled, in practice, by varying the d-c excitation voltage applied to the field winding.

In the design, however, many factors must be taken into account, as the following text illustrates.

As mentioned before, the conductors in a generator armature are arranged in one or more groups called phases, according to whether the machine is designed to deliver single-phase, 2-phase, or 3-phase voltages. The effective voltage, E, per phase is

$$E = 2.22\ \Phi Z f\ 10^{-8}\ K_b\ K_p,$$

where Φ is the number of magnetic lines of flux per pole, Z the number of conductors in series per phase, f the frequency in cycles per second, K_b a breadth (or belt) factor, and K_p a pitch factor.

Generally, the coils of each phase are distributed uniformly around the stator. The voltages generated in the various coils are not in time phase with each other because of the displacement of the coils. A breadth, or belt, factor K_b takes the displacement into account and reduces the total generated voltage per phase below the voltage that would be generated if all the active conductors were in the form of a concentrated winding. Also, if the two halves of a coil are less than 180 electrical degrees apart, the voltage generated in the coil is less than it would be if the coil pitch were a full 180 electrical degrees. The pitch factor, K_p, accounts for this reduction in voltage.

For example, a certain 3-phase, 60-cycle generator has 96 conductors in series per phase and a field pole flux of 2.54×10^6 lines per pole. The breadth factor is 0.958, and the pitch factor is 0.966. The effective voltage per phase is

$$E = \frac{2.22 \times 2.54 \times 10^6 \times 96 \times 60 \times 0.958 \times 0.966}{10^8} = 300 \text{ volts.}$$

CHARACTERISTICS

When the load on a generator is changed, the terminal voltage varies with the load. The amount of variation depends on the design of the generator and the power factor of the load. With a load having a lagging power factor, the drop in terminal voltage with increased load is greater than for unity power factor. With a load having a leading power factor, the terminal voltage tends to rise. The causes of a change in terminal voltage with load change are (1) armature resistance, (2) armature reactance, and (3) armature reaction.

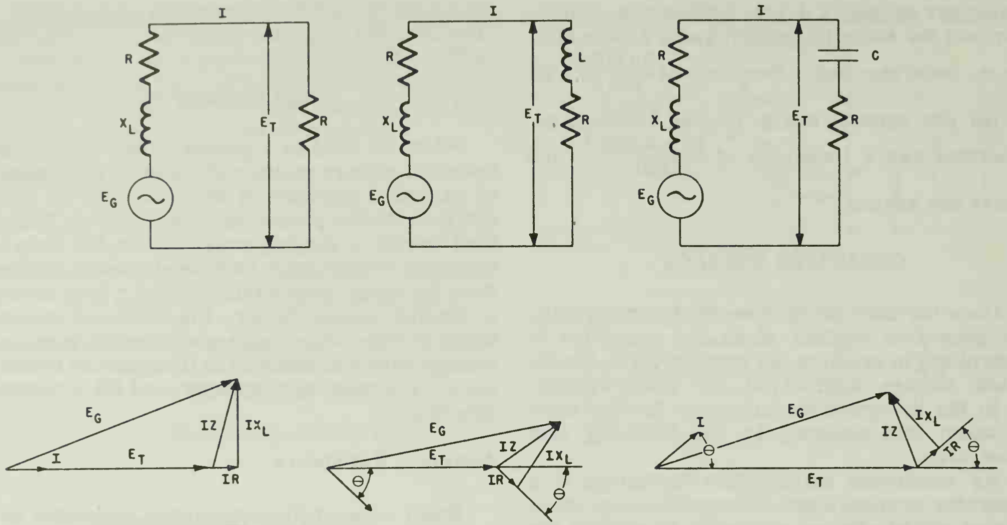
Armature Resistance

When current flows through a generator armature winding, there is an *IR* drop due to the resistance of the winding. This drop increases with load, and the terminal voltage is reduced. The armature resistance drop is small because the resistance is low.

Armature Reactance

The armature current of an a-c generator varies approximately as a sine wave. The continuously varying current in the generator armature is accompanied by an IX_L voltage drop in addition to the *IR* drop. Armature reactance in an a-c generator may be from 30 to 50 times the value of armature resistance because of the relatively large inductance of the coils compared with their resistance.

A simplified series equivalent circuit of one phase of an a-c generator is shown in figure 13-14. The voltage generated in the phase winding is equal to the vector sum of the terminal voltage for the phase and the internal voltage loss in the armature resistance, R, and the armature reactance, X_L, associated with that phase. The voltage vectors for a unity power-factor load are shown in figure 13-14 (A). The armature *IR* drop is in phase with the current, I, and the terminal voltage, E_t. Because the armature IX_L drop is 90° out of phase with the current, the terminal voltage is approximately equal to the generated voltage, less the *IR* drop in the armature.



UNITY POWER FACTOR LOAD

(A)

LAGGING POWER FACTOR LOAD

(B)

LEADING POWER FACTOR LOAD

(C)

Figure 13-14.—A-c generator voltage characteristics.

The voltage vectors for a lagging power-factor load are shown in figure 13-14 (B). The load current and *IR* drop lag the terminal voltage by angle θ. In this example, the armature *IZ* drop is more nearly in phase with the terminal voltage and the generated voltage. Hence, the terminal voltage is approximately equal to the generated voltage, less the armature *IZ* drop. Because the *IZ* drop is much greater than the *IR* drop, the terminal voltage is reduced that much more. The voltage vectors for a leading power-factor load are shown in figure 13-14 (C). The load current and *IR* drop lead the terminal voltage by angle θ. This condition results in an increase in terminal voltage above the value of E_g. The total available voltage of the a-c generator phase is the combined effect of E_g (rotationally induced) and the self-induced voltage (not shown in the vectors). The self-induced voltage, as in any a-c circuit, is caused by the varying field (accompanying the varying armature current) linking the armature conductors. The self-induced voltage always lags the current by 90°; hence, when I leads E_t, the self-induced voltage aids E_g, and E_t increases.

Armature Reaction

When an a-c generator supplies no load, the d-c field flux is distributed uniformly across the air gap. When an a-c generator supplies a reactive load, however, the current flowing through the armature conductors produces an armature magnetomotive force (m.m.f.) that influences the terminal voltage by changing the magnitude of the field flux across the air gap. When the load is inductive, the armature m.m.f. opposes the d-c field and weakens it, thus lowering the terminal voltage. When a leading current flows in the armature, the d-c field is aided by the armature m.m.f. and the flux across the air gap is increased, thus increasing the terminal voltage.

VOLTAGE REGULATION

The voltage regulation of an a-c generator is the change of voltage from full load to no load, expressed in percentage of full-load volts, when the speed and d-c field current are held constant.

$$\text{Percent regulation} = \frac{E_{NL} - E_{fL}}{E_{fL}} \times 100.$$

For example, the no-load voltage of a certain generator is 250 volts and the full-load voltage is 220 volts. The percent regulation is

$$\frac{250 - 220}{220} \times 100 = 13.6 \text{ percent.}$$

PRINCIPLES OF A-C VOLTAGE CONTROL

In an a-c generator, an alternating voltage is induced into the armature windings when magnetic fields of alternating polarity are passed across these windings. The amount of voltage induced into the a-c generator windings depends mainly on three things: the number of conductors in series per winding, the speed at which the magnetic field passes across the winding (generator r.p.m.), and the strength of the magnetic field. Any of these three could conceivably be used to control the amount of voltage induced into the a-c generator windings.

The number of windings, of course, is fixed when the generator is manufactured. Also, if the frequency of a generator's output is required to be of a constant value, then the speed of the rotating field must be held constant. This prevents the use of the generator r.p.m. as a means of controlling the voltage output. Thus, the only practical remaining method for obtaining voltage control is to control the strength of the rotating magnetic field. In some specialized applications, the field is furnished by a permanent magnet. The a-c generator in figure 13-2 uses an electromagnetic field rather than a permanent magnetic type field. The strength of this electromagnetic field may be varied by changing the amount of current flowing through the coil. This is done by varying the amount of voltage applied across the coil. It can be seen that by varying the exciter armature d-c output voltage, the a-c generator field strength is also varied. Thus, the magnitude of the generated a-c voltage depends directly on the value of the exciter output voltage. This relationship allows a relatively large a-c voltage to be controlled by a much smaller d-c voltage.

The next function of the a-c generator that you should understand is how the d-c exciter output voltage is controlled. Voltage control in a d-c generator is obtained by varying the strength of the d-c generator shunt field. This is done by using any of a number of different types of voltage regulators. A device which will vary the exciter shunt field current in accordance with changes in the a-c generator voltage is called an a-c generator voltage regulator. This regulator must also maintain the correct value of exciter shunt field current when no a-c voltage corrective action is required (steady state output). In figure 13-15, note that a pair of connections labeled A-C SENSING INPUT feeds a voltage proportional to the a-c generator output voltage to the A-C VOLTAGE REGULATOR. Note also that a portion of the exciter armature output is connected through the exciter's field rheostat, *RX*, then through the exciter shunt field windings, and finally back to the exciter armature. Obviously, the exciter supplies direct current to its own control field, in addition to the a-c generator field, as determined by the setting of *RX*. The setting of *RX* is controlled by the magnetic strength of the control coil *L*. The magnetic strength of *L* is, in turn, controlled by the voltage across resistor *R*. The voltage across *R* is rectified d. c., and is proportional to the a-c line voltage. (Rectifiers are devices that change a.c. to d.c.)

Thus, the essential function of the voltage regulator is to use the a-c output voltage, which it is designed to control, as a sensing influence to control the amount of current the exciter supplies to its own control field. A drop in the output a-c voltage will change the setting of *RX* in one direction and cause a rise in the exciter control field current. A rise in the output a-c voltage will change the setting of *RX* in the opposite direction and cause a drop in the exciter control field current. These latter two characteristics are caused by actions within the voltage regulator. These characteristics are common to both the resistive and magnetic (magnetic amplifier) types of a-c voltage regulators. Both types of regulators perform the same functions, but accomplish them through different operating principles. A detailed description of the construction and operating principles of any particular type of voltage regulator is best left to courses concerning specific ratings, such as the EM and AE courses.

PARALLEL OPERATION OF A-C GENERATORS

A-c generators are connected in parallel to (1) increase the plant capacity beyond that of a single unit, (2) serve as additional reserve power

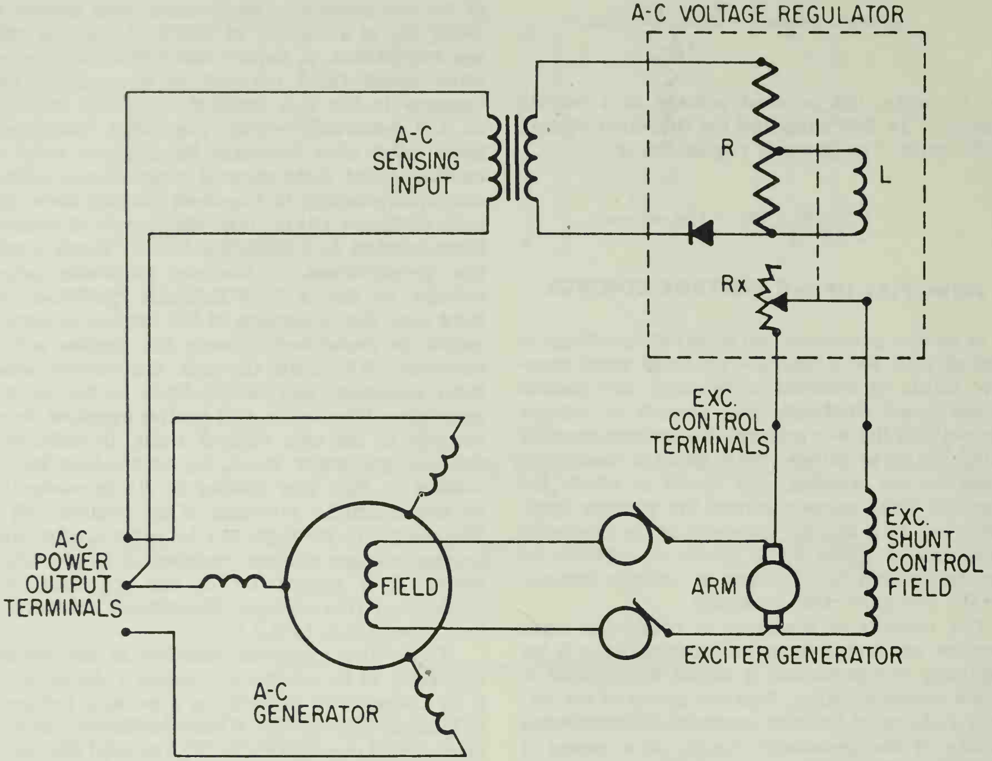


Figure 13-15.—Simplified voltage regulator circuit.

for expected demands, or (3) permit shutting down one machine and cutting in a standby machine without interrupting the power supply. When a-c generators are of sufficient size, and are operating at unequal frequencies and terminal voltages, severe damage may result if they are suddenly connected to each other through a common bus. To avoid this, the generators must be synchronized as closely as possible BEFORE connecting them together. This is done by connecting one generator to the bus (referred to as the BUS GENERATOR), and then sychronizing the other (INCOMING generator) to it before closing the incoming generator's main power contactor. The generators are synchronized when the following conditions are set:

1. Equal terminal voltages. This is obtained by adjustment of the incoming generator's field strength.

2. Equal frequency. This is obtained by adjustment of the incoming generator's prime mover speed.

3. Phase voltages in proper phase relation. (Connecting phase voltages must reach peak values of the same polarity at the same instant.) The generators could have the same frequency, and still not be IN STEP. That is, if the two generators have the same frequency, but one is lagging the other, the lagging generator will remain a fixed number of degrees behind the leading generator, until it is accelerated slightly to CATCH UP.

4. Phases connected in proper sequence. One pair of phases may be properly connected, while the other two pairs may be crossed. In this case, the phase sequence of one generator may be ACB, while the other is ABC.

Synchronizing, A-C Generators

All of the foregoing conditions may be set by the following methods:

Equal voltages may be checked by using a voltmeter. The remaining conditions, equal frequency, phase relations, and phase sequence, are checked by using either synchronizing lamps or a synchroscope. There are a number of ways in which synchronizing lamps may be connected, but the most satisfactory arrangement is the TWO-BRIGHT ONE-DARK method. This connective arrangement is shown in figure 13-16. Note that the lamps are connected directly between the incoming generator's output and the buses. In this way, the two a-c sources may be synchronized before the incoming generator's main power contactor is closed. At the instant the two generators are to be paralleled $L2$ and $L3$ will glow with maximum brilliance and $L1$ will be dark.

Assume that the incoming generator is far out of synchronism—lagging. All three lamps will appear to glow steadily, because the frequency of the voltage across them is the DIFFERENCE in the frequencies of the two generators, and thus is too high for individual alterations to be observed. As the lagging generator is accelerated, however, the lamp (differential) frequency decreases until their light flickers visibly. Their flickering will have a rotating sequence, if connections are correct, and will indicate which generator is faster.

At a point approaching synchronism, lamp $L1$ will be dark because it is connected between like phases. That is, the two phase C voltages will be so nearly synchronized that their differential voltage across $L1$ will be insufficient to make it glow visibly. However, this differential may still be of sufficient magnitude to damage the generators should they be connected at this time. The reason for cross-connecting $L2$ and $L3$ is now indicated. Under perfectly synchronized conditions, the phase voltages across $L2$ and $L3$ are both 120° apart, because of their cross-connection, and both glow with equal brilliance. However, if the generators are not in complete synchronism, but only very near it, one of the bright lamps would be increasing in voltage as the other was decreasing. This action would cause a visible difference in the brilliance of $L2$ and $L3$. Thus, by adjusting the incoming generator's frequency so that no visible difference of brilliance exists between $L2$ and $L3$, the exact point of synchronism can be approached very closely before paralleling the incoming generator with the generator on the bus.

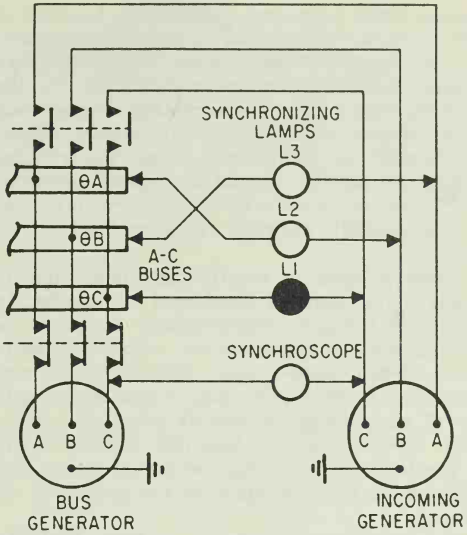


Figure 13-16.—Synchronizing lamp connection for TWO-BRIGHT ONE-DARK method.

When the lamps have been used to get the generators as nearly synchronized as is visibly possible, the synchroscope is used to make the final FINE adjustment to the incoming generator's frequency. A synchroscope is a highly sensitive instrument used to detect a difference in frequency between two a-c sources.

Transformers

A transformer is a device that has no moving parts and that transfers energy from one circuit to another by electromagnetic induction. The energy is always transferred without a change in frequency, but usually with changes in voltage and current. A step-up transformer receives electrical energy at one voltage and delivers it at a higher voltage. Conversely, a stepdown transformer receives energy at one voltage and delivers it at a lower voltage. Transformers require little care and maintenance because of their simple, rugged, and durable construction. The efficiency of transformers is high. Because of this, transformers are responsible for the more extensive use of alternating current than direct current. The conventional constant-potential transformer is designed to operate with the primary connected across a constant-potential source and to provide a secondary voltage that is substantially constant from no load to full load.

Various types of small single-phase transformers are used as shipboard equipment. In many installations, transformers are used on switchboards to stepdown the voltage for indicating lights. Low-voltage transformers are included in some motor control panels to supply control circuits or to operate overload relays. Other common uses include low-voltage supply for gunfiring circuits, special signal lights, and high-voltage ignition circuits for automatic oil burners.

Instrument transformers include POTENTIAL, or VOLTAGE, TRANSFORMERS and CURRENT TRANSFORMERS. Instrument transformers are commonly used with a-c instruments when high voltages or large currents are to be measured.

Electronic circuits and devices employ many types of transformers to provide necessary voltages for proper electron-tube operation, interstage coupling, signal amplification, and so forth. The physical construction of these transformers differs widely.

The POWER-SUPPLY TRANSFORMER used in electronic circuits is a single-phase constant-potential transformer with one or more secondary windings, or a single secondary with several tap connections. These transformers have a low volt-ampere capacity and are less efficient than large constant-potential power transformers. Most power-supply transformers for electronic equipment aboard ship are designed to operate at a frequency of 50 to 60 cycles per second. Aircraft power-supply transformers are designed for a frequency of 400 cycles per second. The higher frequencies permit a saving in size and weight of transformers and associated equipment.

CONSTRUCTION

The typical transformer has two windings insulated electrically from each other. These windings are wound on a common magnetic circuit made of laminated sheet steel. The principal parts are: (1) The CORE, which provides a circuit of low reluctance for the magnetic flux; (2) the PRIMARY WINDING, which receives the energy from the a-c source; (3) the SECONDARY WINDING, which receives the energy by mutual induction from the primary and delivers it to the load, and (4) the ENCLOSURE.

When a transformer is used to step up the voltage, the low-voltage winding is the primary. Conversely, when a transformer is used to step down the voltage, the high-voltage winding is the primary. The primary is always connected to the source of the power; the secondary is always connected to the load. It is common practice to refer to the windings as the primary and secondary rather than the high-voltage and low-voltage windings.

The principal types of transformer construction are the core type and the shell type, as illustrated respectively in figure 13-17 (A) and (B). The cores are built of thin stampings of silicon steel. Eddy currents, generated in the core by the alternating flux as it cuts through the iron, are minimized by using thin laminations and by insulating adjacent laminations with insulating varnish. Hysteresis losses, caused by the friction developed between magnetic particles as they are rotated through each cycle of magnetization, are minimized by using a special grade of heat-treated grain-oriented silicon-steel laminations.

In the core-type transformer, the copper windings surround the laminated iron core. In the shell-type transformer the iron core surrounds the copper windings. Distribution transformers are generally of the core type; whereas some of the largest power transformers are of the shell type.

If the windings of a core-type transformer were placed on separate legs of the core, a relatively large amount of the flux produced by the primary winding would fail to link the secondary winding and a large leakage flux would result. The effect of the leakage flux would be to increase the leakage reactance drop, IX_L, in both windings. To reduce the leakage flux and reactance drop, the windings are subdivided and half of each winding is placed on each leg of the core. The windings may be cylindrical in form and placed one inside the other with the necessary insulation, as shown in figure 13-17 (A). The low-voltage winding is placed with a large part

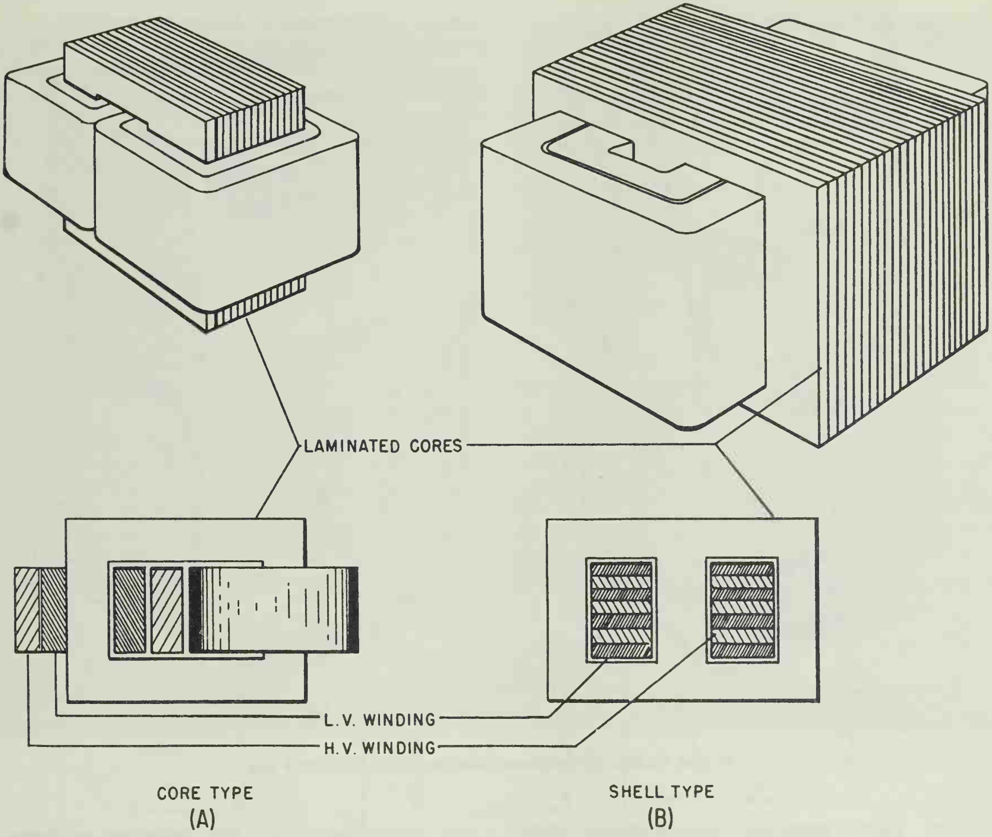


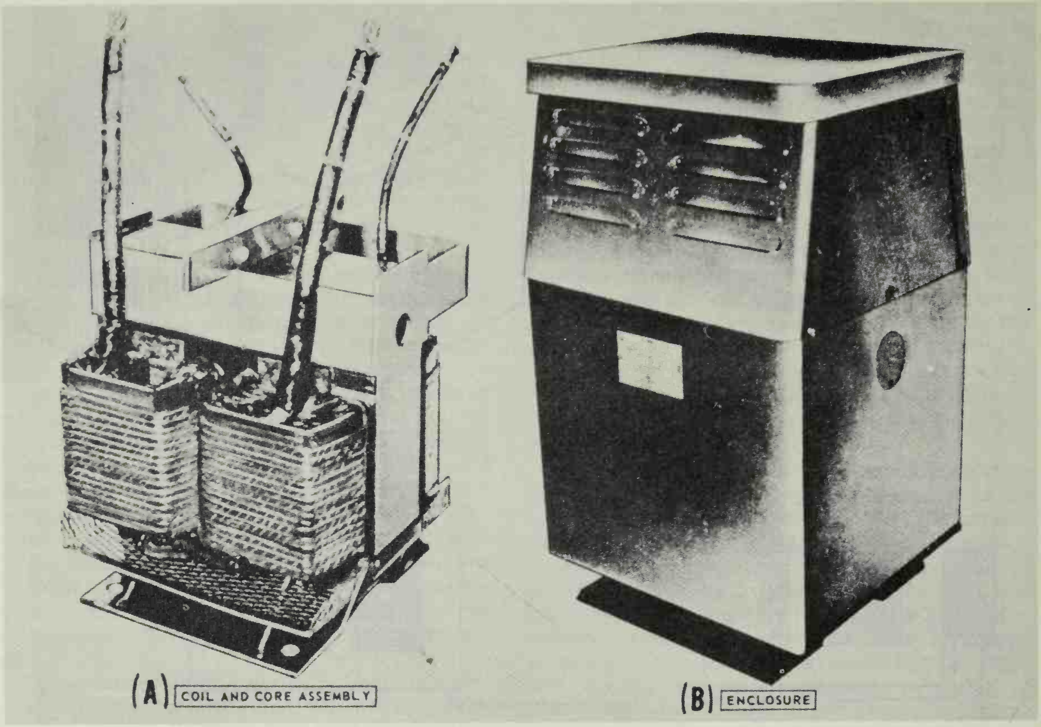
Figure 13-17.—Types of transformer construction.

of its surface area next to the core, and the high-voltage winding is placed outside the low-voltage winding in order to reduce the insulation requirements of the two windings. If the high-voltage winding were placed next to the core, two layers of high-voltage insulation would be required, one next to the core and the other between the two windings.

In another method, the windings are built up in thin flat sections called pancake coils. These pancake coils are sandwiched together, with the required insulation between them, as shown in figure 13-17 (B).

The complete core and coil assembly (fig. 13-18 (A)) is placed in a steel tank. In commercial transformers the complete assembly is usually immersed in a special mineral oil to provide a means of insulation and cooling. No oil is used in the transformer enclosures on naval vessels. Transformer banks installed in these vessels normally consist of single-phase air-cooled transformers mounted in drip-proof enclosures as shown in figure 13-18 (B).

Transformers are built in both single-phase and polyphase units. A 3-phase transformer consists of separate insulated windings for the different phases, wound on a 3-legged core capable of establishing three magnetic fluxes displaced 120° in time phase. Three-phase transformers are not installed aboard ship because the loss of a composite unit would result in an interruption to service. To insure continuity of



(A) COIL AND CORE ASSEMBLY

(B) ENCLOSURE

Figure 13-18.—Single-phase transformer for shipboard use.

service, three separate single-phase delta-connected transformers are installed to supply low-voltage service. If one transformer is damaged in such a system, it can be removed and the remaining two transformers can be operated in the open delta to supply the 3-phase service, but at a reduction in the original load capacity of the transformer bank. Because of the saving in space and weight, 3-phase transformers are often used in high-power airborne radar sets, and these are sometimes immersed in oil.

VOLTAGE AND CURRENT RELATIONS

The operation of the transformer is based on the principle that electrical energy can be transferred efficiently by mutual induction from one winding to another. When the primary winding is energized from an a-c source, an alternating magnetic flux is established in the transformer core. This flux links the turns of both primary and secondary, thereby inducing voltages in them. Because the same flux cuts both windings, the same voltage is induced in each turn of both windings. Hence, the total induced voltage in each winding is proportional to the number of turns in that winding. That is,

$$\frac{E_1}{E_2} = \frac{N_1}{N_2},$$

where E_1 and E_2 are the induced voltages in the primary and secondary windings, respectively, and N_1 and N_2 are the number of turns in the primary and secondary windings, respectively. In ordinary transformers the induced primary voltage is almost equal to the applied primary voltage; hence, the applied primary voltage and the secondary induced voltage are approximately proportional to the respective number of turns in the two windings.

A constant-potential single-phase transformer is represented by the schematic diagram in figure 13-19 (A). For simplicity, the primary winding is shown as being on one leg of the core and the secondary winding on the other leg. The equation for the voltage induced in one winding of the transformer is

$$E = \frac{4.44\ BSfN,}{10^8}$$

where E is the r.m.s. voltage, B the maximum value of the magnetic flux density in lines per square inch in the core, S the cross-sectional area of the core in square inches, f the frequency in cycles per second, and N the number of complete turns in the winding.

For example, if the maximum flux density is 90,000 lines per square inch, the cross-sectional area of the core is 4.18 square inches, the frequency is 60 cycles per second, and the number of turns in the high-voltage winding is 1,100, the voltage rating of this winding is

$$E_1 = \frac{4.44 \times 90{,}000 \times 4.18 \times 60 \times 1{,}100}{10^8} = 1{,}100 \text{ volts.}$$

If the primary-to-secondary turns ratio of this transformer is 10 to 1, the number of turns in the low-voltage winding will be

$$\frac{1{,}100}{10} = 110 \text{ turns,}$$

and the voltage induced in the secondary will be

$$E_2 = \frac{1{,}100}{10} = 110 \text{ volts.}$$

The waveforms of the ideal transformer with no load are shown in figure 13-19 (B). When E_1 is applied to the primary winding, N_1, with the switch, S, open, the resulting current, I_o, is small and lags E_1 by almost 90° because the circuit is highly inductive. This no-load current is called the EXCITING, or MAGNETIZING, CURRENT because it supplies the magnetomotive force that produces the transformer core flux Φ. The flux produced by I_o cuts the primary winding, N_1,

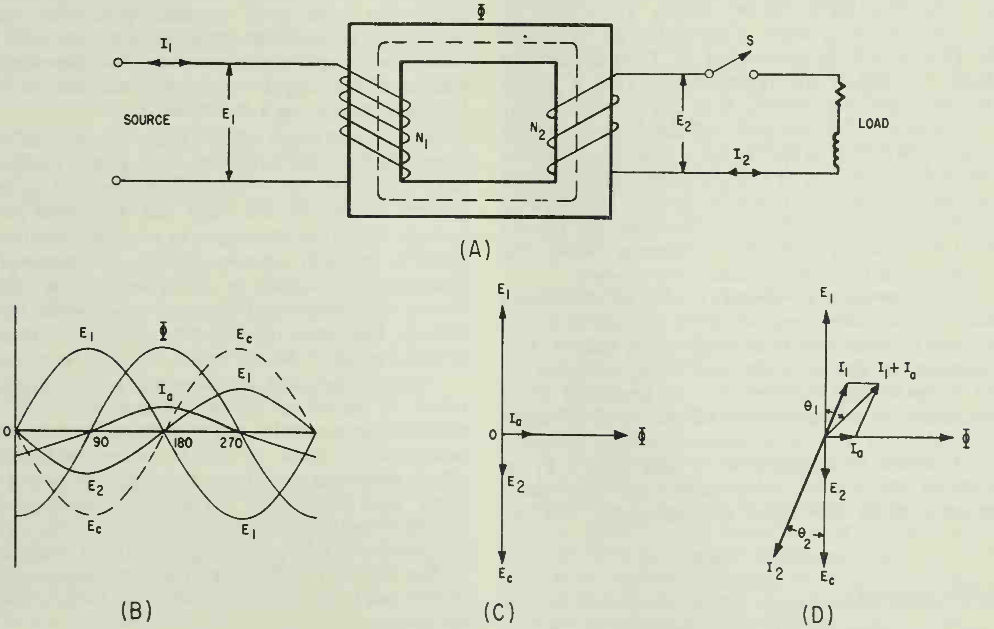


Figure 13-19.—Constant-potential transformer.

and induces a counter voltage E_c 180° out of phase with E_1, in this winding. The voltage, E_2, induced in the secondary winding is in phase with the induced (counter) voltage, E_c, in the primary winding, and both lag the exciting current and flux, whose variations produce them, by an angle of 90°. These relations are shown in vector form in figure 13-19 (C). The values are only approximate and are not drawn exactly to scale.

When a load is connected to the secondary by closing switch S (fig. 13-19 (A)), the secondary current I_2, depends upon the magnitude of the secondary voltage, E_2, and the load impedance, Z. For example, if E_2 is equal to 110 volts and the load impedance is 22 ohms, the secondary current will be

$$I_2 = \frac{E_2}{Z_2} = \frac{110}{22} = 5 \text{ amperes.}$$

If the secondary power factor is 86.6 percent, the phase angle, θ_2, between secondary current and voltage will be the angle whose cosine is 0.866, or 30°.

The secondary load current flowing through the secondary turns comprises a load component of magnetomotive force, which according to Lenz's law is in such a direction as to oppose the flux which is producing it. This opposition tends to reduce the transformer flux a slight amount. The reduction in flux is accompanied by a reduction in the counter voltage induced in the primary winding of the transformer. Because the internal impedance of the primary winding is low and the primary current is limited principally by the counter e.m.f. in the winding, the transformer primary current increases when the counter e.m.f. in the primary is reduced.

The increase in primary current continues until the primary ampere turns are equal to the secondary ampere turns, neglecting losses. For example, in the transformer being considered, the magnetizing current, I_o, is assumed to be negligible in comparison with the total primary current, $I_1 + I_o$, under load conditions because I_o is small in relation to I_1 and lags it by an angle of 60°. Hence, the primary and secondary ampere turns are equal and opposite. That is,

$$N_1 I_1 = N_2 I_2.$$

In this example,

$$I_1 = \frac{N_2}{N_1} I_2 = \frac{110}{1{,}100} \times 5 = 0.5 \text{ ampere.}$$

Neglecting losses, the power delivered to the primary is equal to the power supplied by the secondary to the load. If the load power is $P_2 = E_2 I_2 \cos \theta_2$, or 110 x 5 (cos 30 = 0.866) = 476 watts, the power supplied to the primary is approximately $P_1 = E_1 I_1 \cos \theta$, or 110 x 0.5 (cos 30° = 0.866) = 476 watts.

The load component of primary current, I_1, increases with secondary load and maintains the transformer core flux at nearly its initial value. This action enables the transformer primary to take power from the source in proportion to the load demand, and to maintain the terminal voltage approximately constant. The lagging-power-factor load vectors are shown in figure 13-19 (D). Note that the load power factor is transferred through the transformer to the primary and that θ_2 is approximately equal to θ_1, the only difference being that θ_1 is slightly larger than θ_2 because of the presence of the exciting current which flows in the primary winding but not in the secondary.

The copper loss of a transformer varies as the square of the load current; whereas the core loss depends on the terminal voltage applied to the primary and on the frequency of operation. The core loss of a constant-potential transformer is constant from no load to full load because the frequency is constant and the effective values of the applied voltage, exciting current, and flux density are constant.

If the load supplied by a transformer has unity power factor, the kilowatt (true power) output is the same as the kilovolt-ampere (apparent power) output. If the load has a lagging power factor, the kilowatt output is proportionally less than the kilovolt-ampere output. For example, a transformer having a full-load rating of 100 kv.-a. can supply a 100-kw. load at unity power factor, but only an 80-kw. load at a lagging power factor of 80 percent.

Navy shipboard transformers are generally rated in terms of the kv.-a. load that they can safely carry continuously without exceeding a temperature rise of 80° C. when maintaining rated secondary voltage at rated frequency and when operating with an ambient (surrounding atmosphere) temperature of 40° C. The actual temperature RISE of any part of the transformer is the difference between the total temperature of that part and the temperature of the surrounding air.

It is possible to operate transformers on a higher frequency than that for which they are designed, but it is not permissable to operate them at more than 10 percent below their rated frequency, because of the resulting overheating. The exciting current in the primary varies directly with the applied voltage and, like any impedance containing inductive reactance, the exciting current varies inversely with the frequency. Thus, at reduced frequency, the exciting current becomes excessively large and the accompanying heating may damage the insulation and the windings.

EFFICIENCY

The efficiency of a transformer is the ratio of the output power at the secondary terminals to the input power at the primary terminals. It is also equal to the ratio of the output to the output plus losses. That is,

$$\text{efficiency} = \frac{\text{output}}{\text{input}} = \frac{\text{output}}{\text{output + copper loss + core loss}}$$

The ordinary power transformer has an efficiency of 97 to 99 percent. The losses are due to the copper losses in both windings and the hysteresis and eddy-current losses in the iron core.

The copper losses vary as the square of the current in the windings and as the winding resistance. In the transformer being considered, if the primary has 1,100 turns of number 23 copper wire, having a length of 1,320 feet, the resistance of the primary winding is 26.9 ohms. If the load current in the primary is 0.5 ampere, the primary copper loss is $(0.5)^2 \times 26.9 = 6.725$ watts. Similarly, if the secondary winding contains 110 turns of number 13 copper wire, having a length of approximately 132 feet, the secondary resistance will be 0.269 ohm. The secondary copper loss is $I_2{}^2R_2$, or $(5)^2 \times 0.269 = 6.725$ watts, and the total copper loss is $6.725 \times 2 = 13.45$ watts.

The core losses, consisting of the hysteresis and eddy-current losses, caused by the alternating magnetic flux in the core are approximately constant from no load to full load, with rated voltage applied to the primary.

In the transformer of figure 13-19 (A), if the core loss is 10.6 watts and the copper loss is 13.4 watts, the efficiency is

$$\frac{\text{output}}{\text{output + copper loss + core loss}} =$$

$$\frac{476}{476 + 13.4 + 10.6} = \frac{476}{500} = 0.952,$$

or 95.2 percent. The rating of the transformer is

$$\frac{E_1I_1}{1,000} = \frac{1,100 \times 0.5}{1,000} = 0.55 \text{ kv.-a.}$$

The efficiency of this transformer is relatively low because it is a small transformer and the losses are disproportionately large.

POLARITY MARKING OF TRANSFORMERS

Standard polarity markings and transformer lead color coding are covered in chapter 20 of this course.

SINGLE-PHASE CONNECTIONS

Single-phase distribution transformers usually have their windings divided into two or more sections, as shown in figure 13-20. When the two secondary windings are connected in series (fig. 13-20 (A)), their voltages add. In figure 13-20 (B), the two secondary windings are connected in parallel, and their currents add. For example, if each secondary winding is rated at 115 volts and 100 amperes, the series-connection output rating will be 230 volts at 100 amperes, or 23 kv.-a.; the parallel-connection output rating will be 115 volts at 200 amperes, or 23 kv.-a.

In the series connection, care must be taken to connect the coils so that their voltages add. The proper arrangement is indicated in the figure. A trace made through the secondary circuits from X_1 to X_4 is in the same direction as that of the arrows representing the maximum positive voltages.

In the parallel connection, care must be taken to connect the coils so that their voltages are in opposition. The correct connection is indicated in the figure. The direction of a trace made through the secondary windings from X_1 to X_2 to X_4 to X_3 and returning to X_1 is the same as that of the arrow in the right-hand winding. This condition indicates that the secondary voltages have their positive maximum values in directions opposite to each other in the closed circuit, which is formed by paralleling the two secondary windings. Thus, no circulating current will flow in these windings on no load. If either winding were reversed, a short-circuit current would flow in the secondary, and this would cause the primary to draw a short-circuit current from the source. This action would, of course, damage the transformer as well as the source.

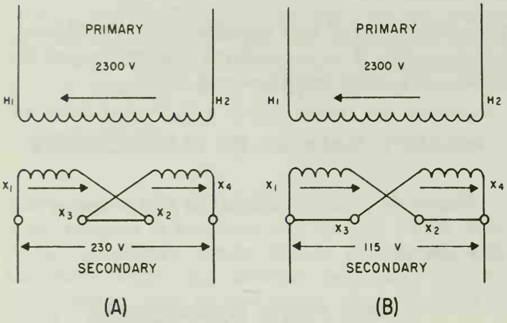


Figure 13-20.—Single-phase transformer secondary connections.

THREE-PHASE CONNECTIONS

Power may be supplied through 3-phase circuits containing transformers in which the primaries and secondaries are connected in various wye and delta combinations. For example, three single-phase transformers may supply 3-phase power with four possible combinations of their primaries and secondaries. These connections are: (1) primaries in delta and secondaries in delta, (2) primaries in wye and secondaries in wye, (3) primaries in wye and secondaries in delta, (4) primaries in delta and secondaries in wye.

Delta and wye connections were described earlier in this chapter under the subject "Three-Phase Generators," and the relations between line and phase voltages and currents were also described. These relations apply to transformers as well as to a-c generators.

If the primaries of three single-phase transformers are properly connected (either in wye or delta) to a 3-phase source, the secondaries may be connected in delta, as shown in figure 13-21. A topographic vector diagram of the 3-phase secondary voltages is shown in figure 13-21 (A). The vector sum of these three voltages is zero. This may be seen by combining any two vectors, for example, E_A and E_B, and noting that their sum is equal and opposite to the 3rd vector, E_C. A voltmeter inserted within the delta will indicate zero voltage, as shown in figure 13-21 (B), when the windings are connected properly.

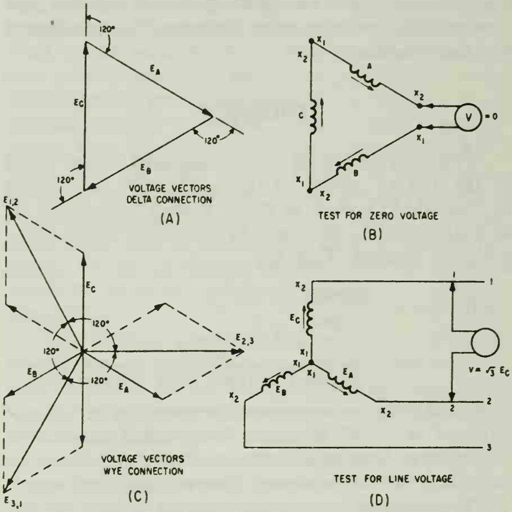


Figure 13-21.—Delta-connected transformer secondaries.

Assuming all three transformers have the same polarity, the delta connection consists in connecting the X_2 lead of winding A to the X_1 lead of B, the X_2 lead of B to X_1 of C, and the X_2 lead of C to X_1 of A. If any one of the three windings is reversed with respect to the other two windings, the total voltage within the delta will equal twice the value of one phase; and if the delta is closed on itself, the resulting current will be of short-circuit magnitude, with resulting damage to the transformer windings and cores. The delta should never be closed until a test is first made to determine that the voltage within the delta is zero or nearly zero. This may be done with a voltmeter, fuse wire, or test lamp. In the figure, when the voltmeter is inserted between the X_2 lead of A and the X_1 lead of B, the delta circuit is completed through the voltmeter, and the indication should be approximately zero. Then the delta is completed by connecting the X_2 lead of A to the X_1 lead of B.

If the three secondaries of an energized transformer bank are properly connected in delta and are supplying a balanced 3-phase load, the line current will be equal to 1.73 times the phase current. If the rated current of a phase (winding) is 100 amperes, the rated line current will be 173 amperes. If the rated voltage of a phase is 120 volts, the voltage between any two line wires will be 120 volts.

The three secondaries of the transformer bank may be reconnected in wye in order to increase the output voltage. The voltage vectors are shown in figure 13-21 (C). If the phase voltage is 120 volts, the line voltage will be 1.73 x 120 = 208 volts. The line voltages are represented by vectors, $E_{1,2}$, $E_{2,3}$, and $E_{3,1}$. A voltmeter test for the line voltage is represented in figure 13-21 (D). If the three transformers have the same polarity, the proper connections for a wye-connected secondary bank are indicated in the figure. The X_1 leads are connected to form a common or neutral connection and the X_2 leads of the three secondaries are brought out to the line leads. If the connections of any one winding are reversed, the voltages between the 3 line wires will become unbalanced, and the loads will not receive their proper magnitude of load current. Also the phase angle between the line currents will be changed, and they will no longer be 120° out of phase with each other. Therefore, it is important to properly connect the transformer secondaries in order to preserve the symmetry of the line voltages and currents.

Transformer installations aboard naval vessels usually consist of 450/117-volt delta-connected banks to supply the general lighting circuits and service for the interior-communications and fire control circuits. Some ships also include 450/230-volt delta-connected banks to supply the galley equipment. Power is distributed over an ungrounded 3-wire, 3-phase, 450-volt system.

Three single-phase transformers with both primary and secondary windings delta connected are shown in figure 13-22. The H_1 lead of one phase is always connected to the H_2 lead of an adjacent phase, the X_1 lead is connected to the X_2 terminal of the corresponding adjacent phase, and so on; and the line connections are made at these junctions. This arrangement is based on the assumption that the three transformers have the same polarity.

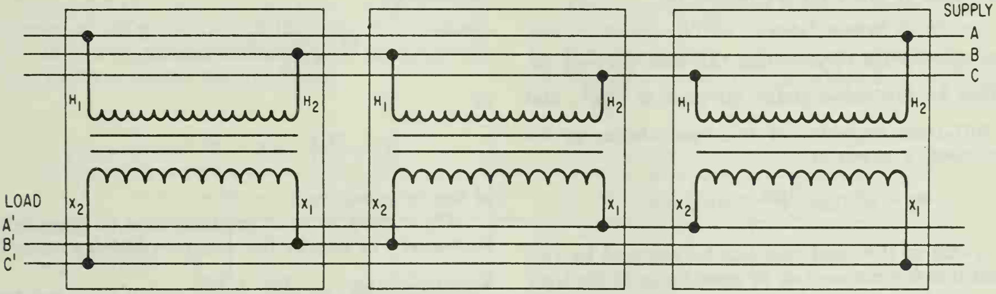


Figure 13-22.—Delta-delta transformer connections.

An open-delta connection results when any one of the three transformers is removed from the delta-connected transformer bank without disturbing the 3-wire 3-phase connections to the remaining two transformers. These transformers will maintain the correct voltage and phase relations on the secondary to supply a balanced 3-phase load. An open-delta connection is shown in figure 13-23. The 3-phase source supplies the primaries of the two transformers, and the secondaries supply a 3-phase voltage to the load.

The LINE CURRENT is equal to the transformer PHASE CURRENT in the open-delta connection. In the closed-delta connection, the transformer phase current, $I_{phase} = \frac{I_{line}}{\sqrt{3}}$. Thus, when one transformer is removed from a delta-connected bank of three transformers, the remaining two transformers will carry a current equal to $\sqrt{3}\ I_{phase}$. This value amounts to an overload current on each transformer of 1.73 times the rated current, or an overload of 73,2 percent.

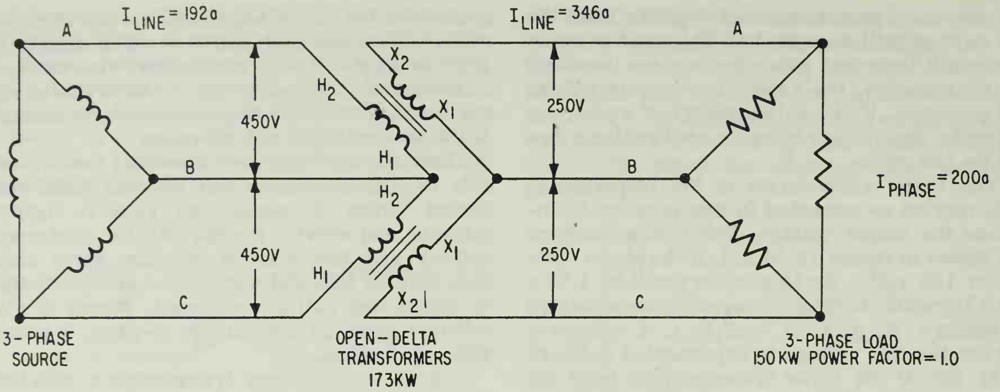


Figure 13-23.—Open-delta transformer connection.

Thus, in an open-delta connection, the line current must be reduced so as not to exceed the rated current of the individual transformers if they are not to be overloaded. The open-delta connection therefore results in a reduction in system capacity. The full-load capacity in a delta connection at unity power factor is

$$P_\Delta = 3I_{phase}E_{phase} = \sqrt{3}E_{line}I_{line}.$$

In an open-delta connection, the line current is limited to the rated phase current of $\frac{I_{line}}{\sqrt{3}}$, and the full-load capacity of the open-delta, or V-connected, system is

$$P_v = \sqrt{3}E_{line}\frac{I_{line}}{\sqrt{3}} = E_{line}I_{line}.$$

The ratio of the load that can be carried by two transformers connected in open delta to the load that can be carried by three transformers in closed delta is

$$\frac{P_v}{P_\Delta} = \frac{E_{line}I_{line}}{\sqrt{3}E_{line}I_{line}} = \frac{1}{\sqrt{3}} = 0.577, \text{ or } 57.7 \text{ percent}$$

of the closed-delta rating.

For example, a 150-kw. 3-phase balanced load operating at unity power factor is supplied at 250 volts. The rating of each of three transformers in closed delta is $\frac{150}{3}$ = 50 kw., and the phase current is $\frac{50,000}{250}$ = 200 amperes. The line current is 200$\sqrt{3}$=346 amperes. If one transformer is removed from the bank, the remaining two transformers would be overloaded 346 - 200 =146 amperes, or $\frac{146}{200}$ x 100 = 73 percent. To prevent overload on the remaining two transformers, the line current must be reduced from 346 amperes to 200 amperes and the total load reduced to

$$\frac{\sqrt{3}\times 250\times 200}{1,000} = 86.6 \text{ kw.,}$$

or

$$\frac{86.6}{150}\times 100 = 57.7 \text{ percent}$$

of the original load.

The rating of each transformer in open delta necessary to supply the original 150-kw. load is $\frac{E_{phase}I_{phase}}{1,000}$, or $\frac{250 \times 346}{1,000}$ = 86.6 kw., and two transformers require a total rating of 2 x 86.6 = 173.2 kw., compared with 150 kw. for three transformers in closed delta. The required increase in transformer capacity is 173.2 - 150 =23.2 kw., or $\frac{23.2}{150}$ x 100 = 15.5 percent, when two transformers are used in open delta to supply the same load as three 50-kw. transformers in closed delta.

Three single-phase transformers with both primary and secondary windings wye connected are shown in figure 13-24. Only 57.7 percent of the line voltage ($\frac{E_{line}}{\sqrt{3}}$) is impressed across each

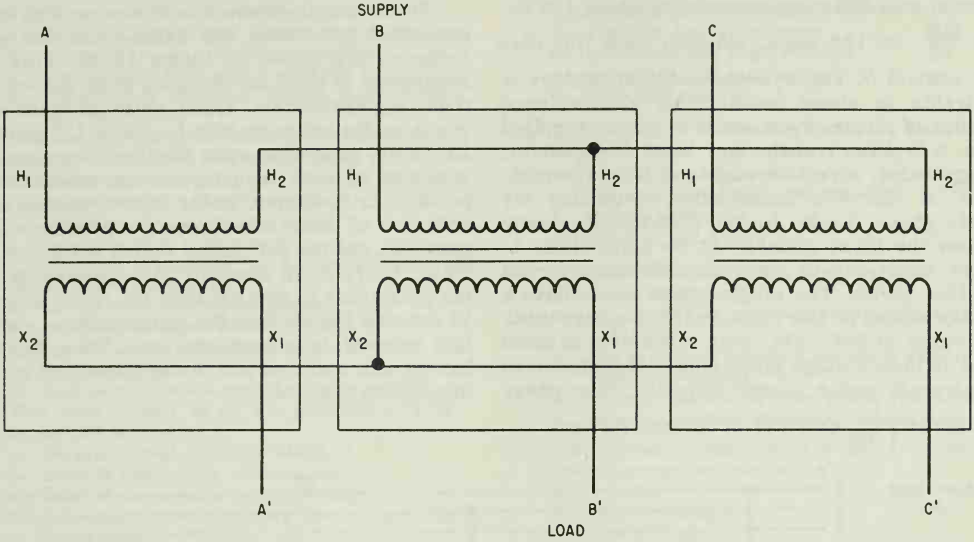

SUPPLY
A
B
C
H1
H2
H1
H2
H1
H2
X2
X1
X2
X1
X2
X1
A'
B'
C'
LOAD

Figure 13-24.—Wye-wye transformer connections.

winding, but full-line current flows in each transformer winding. Although the wye-wye connection is never used aboard ship, it is frequently used in Navy shore installations.

Three single-phase transformers delta connected to the primary circuit and wye connected to the secondary circuit are shown in figure 13-25. This connection provides 4-wire, 3-phase

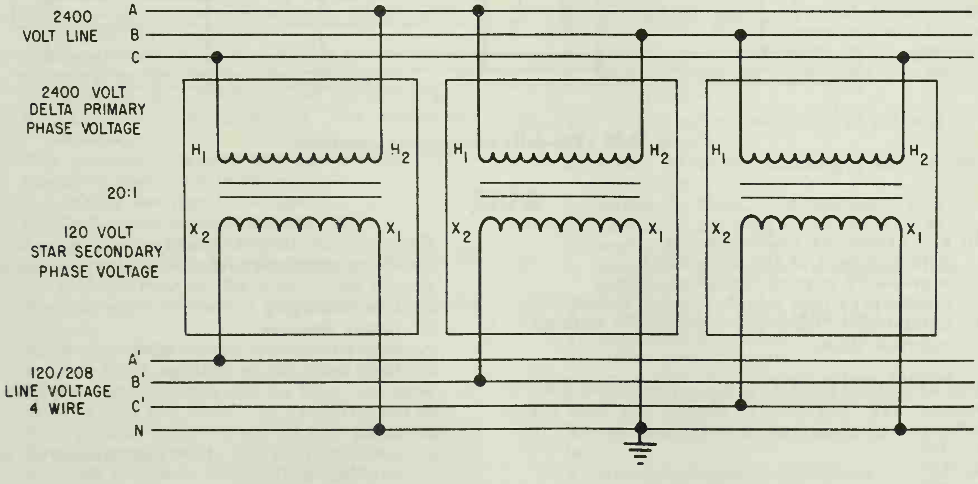

2400
VOLT LINE
A
B
C
2400 VOLT
DELTA PRIMARY
PHASE VOLTAGE
H1
H2
H1
H2
H1
H2
20:1
120 VOLT
STAR SECONDARY
PHASE VOLTAGE
X2
X1
X2
X1
X2
X1
120/208
LINE VOLTAGE
4 WIRE
A'
B'
C'
N

Figure 13-25.—Delta-wye transformer connections.

service with 208 volts between line wires *A'B'C'*, and $\frac{208}{\sqrt{3}}$, or 120 volts, between each line wire and neutral *N*. The wye-connected secondary is desirable in shore installations when a large number of single-phase loads are to be supplied from a 3-phase transformer bank. The neutral, or grounded, wire is brought out from the midpoint of the wye connection, permitting the single-phase loads to be distributed evenly across the three phases. At the same time, 3-phase loads can be connected directly across the line wires. The single-phase loads have a voltage rating of 120 volts, and the 3-phase loads are rated at 208 volts. This connection is often used in high-voltage plate-supply transformers in aircraft radar power supplies. The phase voltage is $\frac{1}{1.73}$, or 0.577 of the line voltage.

Three single-phase transformers with wye-connected primaries and delta-connected secondaries are shown in figure 13-26. This arrangement is used for stepping down the voltage from approximately 4,000 volts between line wires on the primary side to either 115 volts or 230 volts, depending upon whether the secondary windings of each transformer are connected in parallel or in series. In the figure, the two secondaries of each transformer are connected in parallel, and the secondary output voltage is 115 volts. There is an economy in transmission with the primaries in wye because the line voltage is 73 percent higher than the phase voltage, and the line current is accordingly less. Thus, the line losses are reduced and the efficiency of transmission is improved.

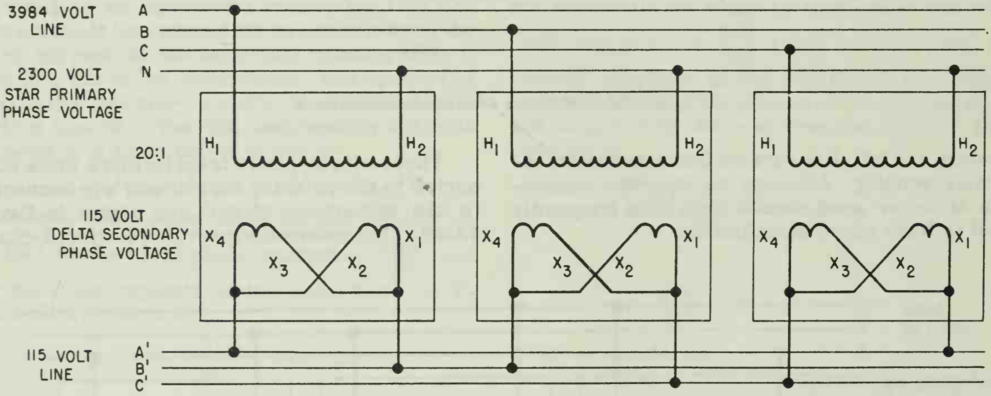

3984 VOLT LINE
A
B
C
N
2300 VOLT STAR PRIMARY PHASE VOLTAGE
20:1
H₁
H₂
115 VOLT DELTA SECONDARY PHASE VOLTAGE
X₄
X₃
X₂
X₁
115 VOLT LINE
A'
B'
C'

Figure 13-26.—Wye-delta transformer connections.

QUIZ

1. An a-c armature is always the
   a. rotating part of the generator
   b. stationary part of the generator
   c. conductors into which voltage is induced
   d. conductors through which d-c exciter current flows

2. The armature windings of a 2-phase a-c generator are physically placed so that the induced voltages are out of phase by
   a. 30°
   b. 60°
   c. 90°
   d. 120°

3. When connecting a 3-phase a-c generator for delta operation, the delta closure voltage should be
   a. line voltage
   b. phase voltage
   c. approximately zero volts
   d. less than phase voltage

4. With no load on the secondary, the current in the primary is
   a. zero
   b. limited only by the resistance of the winding
   c. determined by c.e.m.f. of secondary
   d. determined by c.e.m.f. of primary

5. The a-c field is always the
   a. rotating part of the generator
   b. stationary part of the generator
   c. conductors into which voltage is induced
   d. conductors through which d-c exciter current flows

6. The voltage induced into the armature windings is maximum when the field poles are
   a. in the neutral plane
   b. opposite the armature poles
   c. between the armature poles
   d. rotating at a high speed

7. The output frequency of an a-c generator is dependent upon the
   a. number of poles and phases
   b. rotor speed and phases
   c. number of poles and the speed of the prime mover
   d. number of poles and the rotor speed

8. The load rating of an a-c generator is determined by the
   a. internal heat it can withstand
   b. load it can carry continuously
   c. load it is capable of supplying
   d. overload it can carry for a specified time only

9. In a 2-phase 3-wire a-c generator, the formula for line voltage is
   a. $E_L = \frac{E_p}{\cos 45^\circ}$
   b. $E_L = \frac{E_p}{\tan 45^\circ}$
   c. $E_L = E_p \times 0.707$
   d. $E_L = E_p \times 1.73$

10. The voltage output of an a-c generator is controlled by
   a. regulating the speed of the prime mover
   b. varying the d-c exciter voltage
   c. varying the reluctance of the air gap
   d. shorting out part of the armature windings

11. The primary reason for connecting transformers wye-wye is to
   a. double the input voltage
   b. double the primary current
   c. invert the frequency
   d. decrease line losses by high voltage with low current in the line

12. The purpose of the d-c generator is to excite the
   a. a-c armature
   b. a-c field
   c. d-c armature
   d. a-c and d-c field

13. A 3-phase wye-connected a-c generator is used to produce
   a. high current, low voltage
   b. low current, low voltage
   c. low current, high voltage
   d. high current, high voltage

14. Two types of instrument transformers are
   a. step-up and step-down
   b. potential and high voltage
   c. potential and current
   d. auto and power

15. The output of a rotating field a-c generator is taken from
   a. sliprings and brushes
   b. commutator bars and brushes
   c. fixed terminals
   d. none of the above

16. Aircraft transformers are designed for 400 c.p.s. because
   a. of the 400-c.p.s. supply available in the aircraft
   b. the higher frequency permits savings of size and weight
   c. it is more stable than lower frequencies
   d. it has a higher average current flow

17. The closure voltage of a delta-connected transformer secondary is
   a. 0 volts
   b. phase voltage
   c. line voltage
   d. line voltage x 1.73

18. The revolving field type a-c generator is most widely used because of
   a. low armature current
   b. improved safety features
   c. low field current through fixed terminals
   d. high power from armature through sliprings

19. When using an a-c generator on a 3-phase 4-wire system, the neutral wire
   a. maintains equal current in each phase
   b. maintains equal power in each phase
   c. maintains equal voltage in each phase
   d. has no current flow when the loads are unbalanced

20. The three principal parts of a transformer are its
   a. core, primary windings, and secondary windings
   b. primary, load, and magnetic flux
   c. primary windings, secondary windings, and magnetic flux
   d. mutual induction, magnetic flux, and windings

21. A-c generators are classified
   a. as to construction
   b. as to power output
   c. according to type of prime mover
   d. according to load connections

22. The principle of operation of a transformer is
   a. electromagnetic induction
   b. varying a conductor in a magnetic field
   c. mutual induction
   d. thermionic emission

CHAPTER 14

ALTERNATING-CURRENT MOTORS

Most of the power generating systems ashore and afloat produce alternating current. Thus, it follows that a great majority of the motors used throughout the Navy are designed to operate on alternating current. However, there are other advantages in the use of a-c motors besides the wide availability of a-c power. In general, a-c motors are less expensive than d-c motors. Some types of a-c motors do not employ brushes and commutators. This eliminates many problems of maintenance and wear; in addition, it eliminates the problem of dangerous sparking.

D-c motors are best suited for some uses, such as applications that require variable-speed motors. However, in the great majority of applications, the a-c motor is best.

A-c motors are manufactured in many different sizes, shapes, and ratings, for use on an even greater number of jobs. They are designed for use with either polyphase or single-phase power systems.

This chapter cannot possibly cover all aspects of the subject of a-c motors. Consequently, it will deal mainly with the operating principles of only the two most common types—the rotating-field induction motor and the synchronous motor.

The Rotating Field

The rotating field is set up by out-of-phase currents in the stator windings. Figure 14-1 illustrates the manner in which a rotating field is produced by stationary coils, or windings, when they are supplied by a 3-phase current source. For purpose of explanation, rotation of the field is developed in the figure by "stopping" it at six selected positions, or instants. These instants are marked off at 60 degree intervals on the sine waves representing currents in the three phases *A*, *B*, and *C*.

At instant 1 the current in phase *B* is maximum positive. (Assume plus 10 amperes in this example.) Current is considered to be positive when it is flowing out from a motor terminal, and negative when it flows into a motor terminal. At the same time (instant 1) current flows into the A and C terminals at half value (minus 5 amperes each in this case). These currents combine at the neutral (common connection) to supply plus 10 amperes out through the *B* phase.

The resulting field at instant 1 is established downward and to the right as shown by the arrow NS. The major portion of this field is produced by the *B* phase (full strength at this time) and is aided by the adjacent phases *A* and *C* (half strength). The weaker portions of the field are indicated by the letters "n" and "s". The field is a two-pole field extending across the space that would normally contain the rotor.

At instant 2 the current in phase *B* is reduced to half value (plus 5 amperes in this example). The current in phase *C* has reversed its flow from minus 5 amperes to plus 5 amperes, and the current in phase *A* has increased from minus 5 to minus 10 amperes.

The resulting field at instant 2 is now established upward and to the right as shown by arrow NS. The major portion of the field is produced by phase *A* (full strength) and the weaker portions by phases *B* and *C* (half strength).

At instant 3 the current in phase *C* is plus 10 amperes and the field extends vertically upward; at instant 4 the current in phase *B* becomes minus 10 amperes and the field extends upward and to the left; at instant 5 the current in phase *A* becomes plus 10 amperes and the field extends downward and to the left; at instant 6 the current in phase *C* is minus 10 amperes and the field extends vertically downward. Instant 7 (not shown) corresponds to instant 1 when the field again extends downward and to the right.

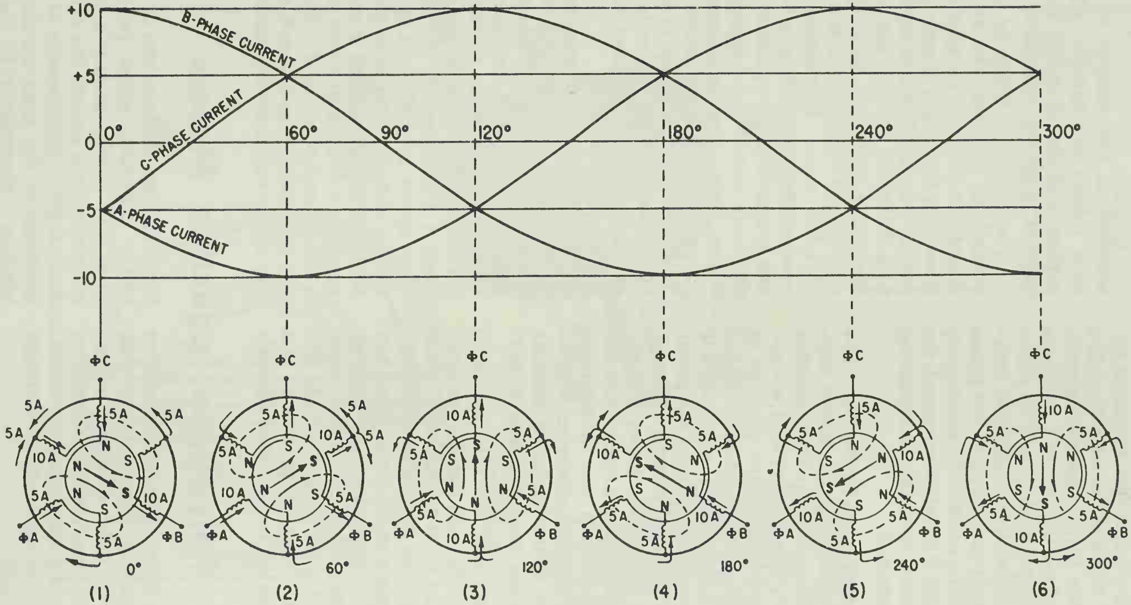

+10
+5
0
-5
-10
B-PHASE CURRENT
C-PHASE CURRENT
A-PHASE CURRENT
0°
60°
90°
120°
180°
240°
300°
ΦA
ΦB
ΦC
N
S
5A
10A
(1)
(2)
(3)
(4)
(5)
(6)

Figure 14-1.—Development of a rotating field.

Thus a full rotation of the two-pole field has been accomplished through one full cycle of 360 electrical degrees of the three-phase currents flowing in the windings.

The direction of rotation of the magnetic revolving field may be changed by interchanging any two line leads to the three motor terminals. For example, in figure 14-2 (A), if line 1 connects to phase *a*, line 2 to phase *b*, and line 3 to phase *c*, and the line currents reach their positive maximum values in the sequence 1, 2, 3, the phase sequence is *a*, *b*, *c* and the rotation is arbitrarily clockwise. If lines 1 and 2 are interchanged, the phase sequence becomes *b*, *a*, *c*, and the revolving field turns counterclockwise.

Most induction motors used by the Navy are designed to operate on single-phase power supplies, or the 3-phase supply used in the preceding discussion. The out-of-phase currents necessary to produce a rotating field are inherent in the 2-phase power supply, since 2-phase voltages are generated 90° apart. When a single-phase supply is used, it is necessary to split the power supply into two separate coil groups. The required phase difference is then generally obtained by inserting capacitance in series with one of the groups (other methods are sometimes used). This causes the single-phase or "split-phase" motor to have characteristics similar in many respects to the true 2-phase motor.

In figure 14-1, note that the sine waves of current traversed 300° through the six positions shown. Accordingly, the field rotated 300°. If the supplied current completes 60 cycles each second, the field would rotate at 60 revolutions per second (60 x 60 = 3,600 revolutions per minute). However, if the number of stator coils were doubled, producing a 4-pole field, the field will rotate only half as fast. Thus, it can be seen that the speed of the revolving field varies directly as the frequency of the applied voltage and inversely as the number of poles.

Thus,

$$N = \frac{120f}{P},$$

where N is the number of revolutions that the field makes per minute, f the frequency of the applied voltage in cycles per second, and P the number of poles produced by the 3-phase winding.

The speed at which an induction motor field rotates is referred to as its SYNCHRONOUS speed, because it is synchronized to the frequency of the power supply at all times. A motor having a 2-pole 3-phase stator winding connected to a 60-cycle source has a synchronous speed (magnetic revolving field speed) of 3,600 r.p.m. A 2-pole 25-cycle motor has a synchronous speed of 1,500 r.p.m. Increasing the number of poles lowers the speed. Thus, a 4-pole 25-cycle motor has a synchronous speed of 750 r.p.m. A 12-pole 60-cycle motor has a synchronous speed of 600 r.p.m. Increasing the frequency of the line supply increases the speed with which the field revolves. Thus, if the frequency is increased from 50 to 60 cycles, and the motor has 4 poles, the speed of the field is increased from 1,500 r.p.m. to 1,800 r.p.m.

The speed of the rotating field is always independent of load changes on the motor, provided the line frequency is maintained constant. The magnetic revolving field always runs at the same speed, pole for pole, as the a-c generator supplying it. If a 2-pole 60-cycle a-c generator supplies a 2-pole motor, the motor has a synchronous speed of 3,600 r.p.m. which is the same as the speed of the a-c generator. If a 4-pole 60-cycle a-c generator runs at 1,800 r.p.m. and supplies a 4-pole 60-cycle motor, the motor has a synchronous speed of 1,800 r.p.m. If this same a-c generator supplies an 8-pole 60-cycle motor, the motor has a synchronous speed of 900 r.p.m.

Polyphase Induction Motors

The driving torque of both d-c and a-c motors is derived from the reaction of current-carrying conductors in a magnetic field. In the d-c motor, the magnetic field is stationary and the armature, with its current-carrying conductors, rotates. The current is supplied to the armature through a commutator and brushes.

In induction motors, the rotor currents are supplied by electro-magnetic induction. The stator windings contain two or more out-of-time-phase currents, which produce corresponding m.m.f.'s. These m.m.f.'s establish a rotating magnetic field across the air gap. This magnetic field rotates continuously at constant speed regardless of the load on the motor. The stator winding corresponds to the armature winding of a d-c motor or to the primary winding of a transformer. The rotor is not connected electrically to the power supply. The induction motor

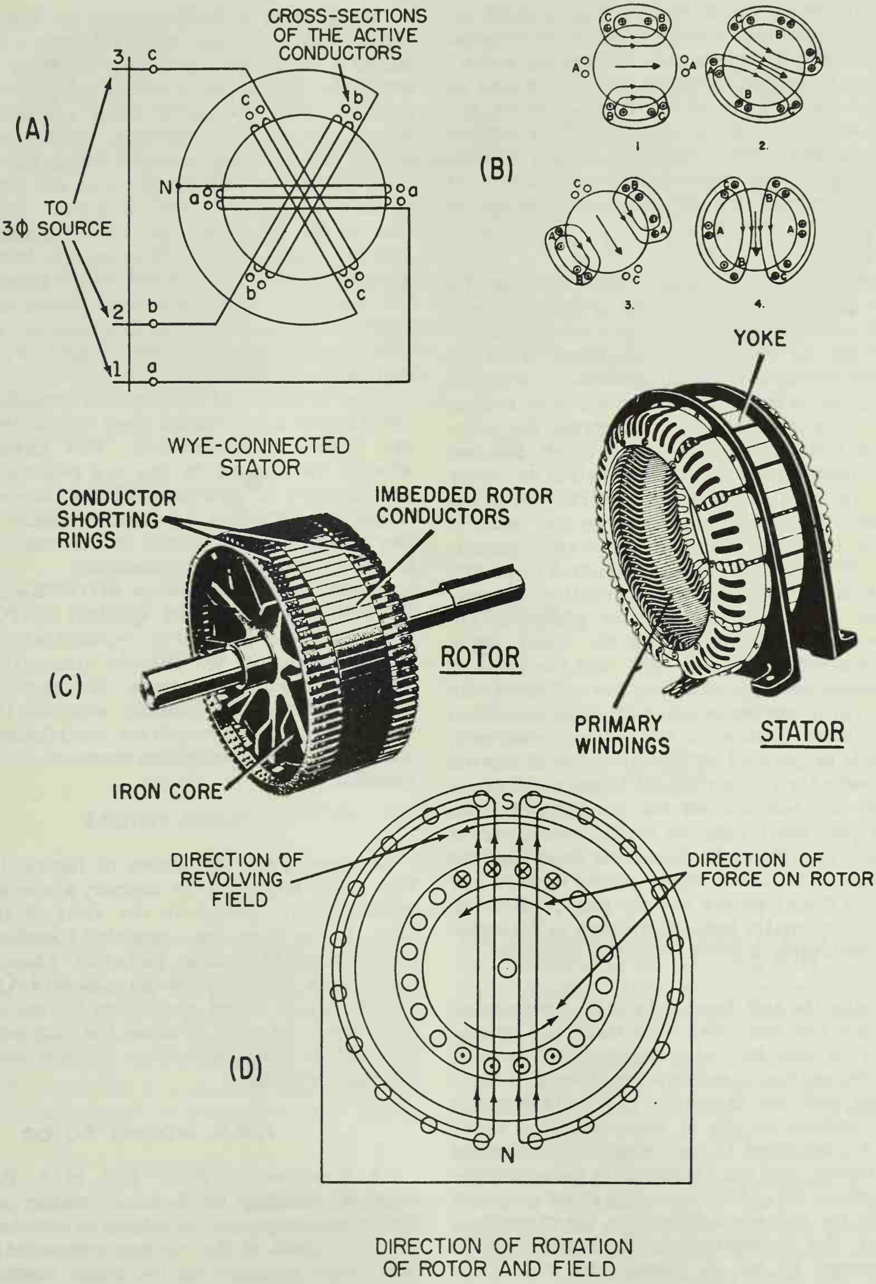

(A)
CROSS-SECTIONS OF THE ACTIVE CONDUCTORS
3
c
2
b
1
a
N
TO 3Φ SOURCE
WYE-CONNECTED STATOR
(B)
1.
2.
3.
4.
A
B
C
(C)
CONDUCTOR SHORTING RINGS
IMBEDDED ROTOR CONDUCTORS
ROTOR
IRON CORE
YOKE
PRIMARY WINDINGS
STATOR
(D)
S
N
DIRECTION OF REVOLVING FIELD
DIRECTION OF FORCE ON ROTOR
DIRECTION OF ROTATION OF ROTOR AND FIELD

Figure 14-2.—Three-phase induction motor.

derives its name from the fact that mutual induction (transformer action) takes place between the stator and the rotor under operating conditions. The magnetic revolving field produced by the stator cuts across the rotor conductors, inducing a voltage in the conductors. This induced voltage causes rotor current to flow. Hence, motor torque is developed by the interaction of the rotor current and the magnetic revolving field.

Figure 14-2 (A) represents the winding of a 3-phase induction motor stator. Part (B) shows how the active stator conductors produce a rotating field, as previously described. Part (C) shows the essential parts of both stator and rotor. The purpose of the iron rotor core is to reduce air gap reluctance and to concentrate the magnetic flux through the rotor conductors. Induced current flows in one direction in half of the rotor conductors, and in the opposite direction in the remainder. The shorting rings on the ends of the rotor complete the path for rotor current. In part (D) a 2-pole field is assumed to be rotating in a counterclockwise direction at synchronous speed. At the instant pictured, the south pole field cuts across the upper rotor conductors from right to left, and the lines of force extend upward. Applying the left-hand rule for generator action to determine the direction of the voltage induced in the rotor conductors, the thumb is pointed in the direction of motion of the conductors with respect to the field. Since the field sweeps across the conductors from right to left, their relative motion with respect to the field is to the right. Hence the thumb points to the right. The index finger points upward and the second finger points into the page, indicating that the rotationally induced voltage in the upper rotor conductors is away from the observer.

Applying the left-hand rule to the lower rotor conductors and the north-pole field, the thumb points to the left, the index finger points upward, and the second finger points toward the observer, indicating that the direction of the rotationally induced voltage is out of the page. The rotor bars are connected to end rings that complete their circuits, and the rotationally induced voltages act in series addition to cause rotor currents to flow in the rotor conductors in the directions indicated. For simplification, the rotor currents are assumed to be in phase with the rotor voltages.

Motor action is analyzed by applying the right-hand rule for motors to the rotor conductors in figure 14-2 (D), to determine the direction of the force acting on the rotor conductors. For the upper rotor conductors, the index finger points upward, the second finger points into the page and the thumb points to the left, indicating that the force on the rotor tends to turn the rotor counterclockwise. This direction is the same as that of the rotating field. For the lower rotor conductors the index finger points upward, the second finger points toward the observer, and the thumb points toward the right, indicating that the force tends to turn the rotor counterclockwise—the same direction as that of the field.

The STATOR of a polyphase induction motor consists of a laminated steel ring with slots on the inside circumference. The motor stator winding is similar to the a-c generator stator winding and is generally of the two-layer distributed preformed type. Stator phase windings are symmetrically placed on the stator and may be either wye or delta connected.

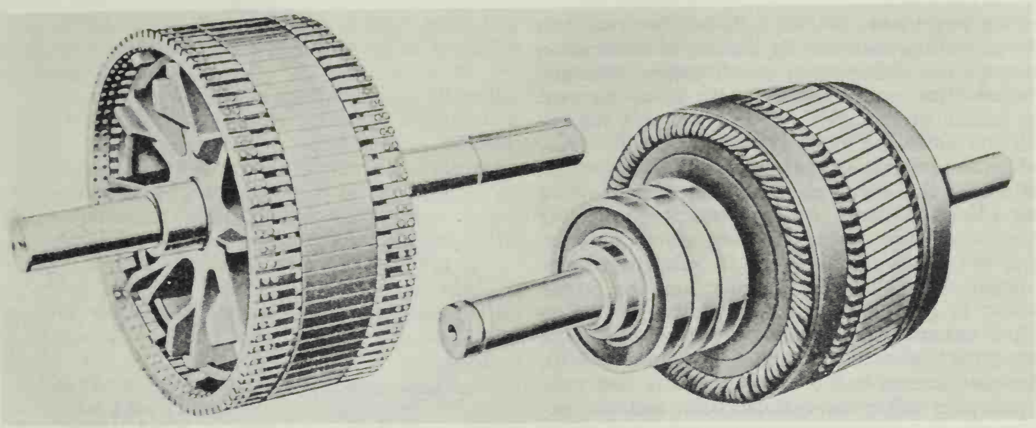
There are two types of ROTORS—the CAGE ROTOR and the FORM-WOUND ROTOR. Both types have a laminated cylindrical core with parallel slots in the outside circumference to hold the windings in place. The cage rotor has an uninsulated bar winding; whereas the form-wound rotor has a two-layer distributed winding with preformed coils like those on a d-c motor armature.

CAGE ROTORS

A cage rotor is shown in figure 14-3 (A). The rotor bars are of copper, aluminum, or a suitable alloy placed in the slots of the rotor core. These bars are connected together at each end by rings of similar material. The conductor bars carry relatively large currents at low voltage. Hence, it is not necessary to insulate these bars from the core because the currents follow the path of least resistance and are confined to the cage winding.

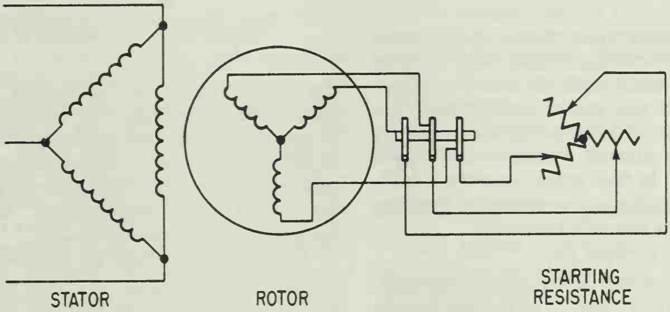
FORM-WOUND ROTOR

A form-wound rotor (fig. 14-3 (B)) has a winding similar to 3-phase stator windings. Rotor windings are usually wye connected with the free ends of the winding connected to three slip rings mounted on the rotor shaft. An external variable wye-connected resistance (fig.



(A) CAGE ROTOR

(B) FORM-WOUND ROTOR



(C) EXTERNAL VARIABLE RESISTANCE

Figure 14-3.–Induction motor rotors.

14-3 (C)) is connected to the rotor circuit through the sliprings. The variable resistance provides a means of increasing the rotor-circuit resistance during the starting period to produce a high starting torque. As the motor accelerates, the rheostat is cut out. When the motor reaches full speed, the sliprings are short-circuited and the operation is similar to that of the cage motor.

TORQUE

As previously described, the revolving field produced by the stator windings cuts the rotor conductors and induces voltages in the conductors. Rotor currents flow because the rotor end-rings provide continuous metallic circuits. The resulting torque tends to turn the rotor in the direction of the rotating field. This torque is proportional to the product of the rotor current, the field strength, and the rotor power factor.

The simplified cross section of a 2-pole cage-rotor motor is shown in figure 14-4. The magnetic field is rotating in a clockwise direction. Applying the left-hand rule for generator action, note that in figure 14-4 (A), the induced currents flow outward in the upper half and inward in the lower half of the rotor conductors. Applying the right-hand rule for motor action, note that the force acting on the rotor conductors is to the right on the upper group and to the left on the lower group.

As previously stated, a d-c motor receives its armature current by means of conduction through the commutator and brushes; whereas an induction motor receives its rotor current by means of induction. In this respect the induction motor is like a transformer with a rotating secondary. The primary is the stator which produces the revolving field; the secondary is the rotor. At start, the frequency of the rotor current is that of the primary stator winding. The reactance of the rotor is relatively large compared with its resistance, and the power factor is low and lagging by almost 90°. The rotor current therefore lags the rotor voltage by approximately 90°, as shown in figure 14-4(B). Because almost half of the conductors under the south pole carry current outward and the remainder of the conductors carry current inward, the net torque on the rotor as a result of the interaction between the rotor and the rotating field is small.

As the rotor comes up to speed in the same direction as the revolving field, the rate at which the revolving field cuts the rotor conductors is reduced and the rotor voltage and frequency of rotor currents are correspondingly reduced. Hence, at almost synchronous speed the voltage induced in the rotor is very small. The rotor reactance, X_L, also approaches zero, as may be seen from the relationship

$$X_L = 2\pi f_o LS,$$

where f_o is the frequency of the stator current, L the rotor inductance, and S the ratio of the difference in speed (between the stator field and the rotor) to the synchronous speed—that is, the slip. Slip is expressed mathematically as

$$S = \frac{N_s - N_r}{N_s},$$

where N_S is the number of revolutions per minute of the stator field, and N_r the number of revolutions per minute of the rotor. The frequency of the induced rotor current is f_oS.

In figure 14-4 (A), the rotor current is nearly in phase with the rotor voltage, and the direction of flow under the south pole is the same in all conductors. The torque would be ideally high except for the very small rotor current, which is produced by the low rotor voltage. The rotor voltage is proportional to the difference in speed between the rotor and the rotating field —that is, proportional to the slip.

The frequency of the rotor current varies directly with the slip. Thus, when the slip and the frequency of rotor current are almost zero, the rotor reactance and angle of lag are very small. When the rotor is starting, the difference in speed between the rotor and the rotating field is maximum; hence, the rotor reactance is maximum because the frequency of rotor current is maximum and approaches that of the line supplying the stator primary.

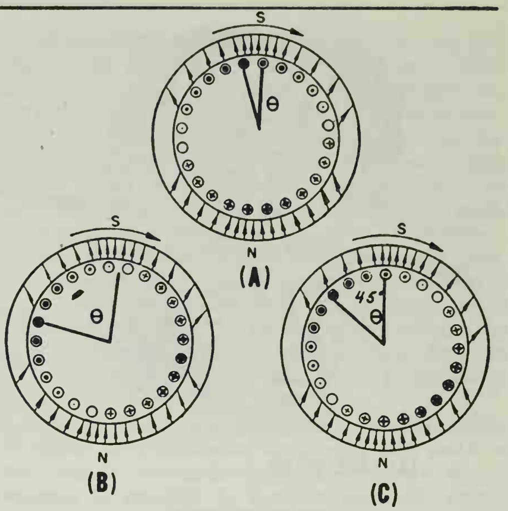


Figure 14-4.—Development of torque.

Normal operation is between these two extremes of rotor slip—that is, when the rotor is not turning at all or when it is turning almost at synchronous speed. The motor speed under normal load conditions is rarely more than 10 percent below synchronous speed. At the extreme of 100 percent slip, the rotor reactance is so high that the torque is low because of low power factor. At the other extreme of zero rotor slip, the torque is low because of low rotor current. The equation for torque, T, is

$$T = K\Phi I_r \cos\theta_r,$$

Where K is a constant, Φ the strength of the magnetic revolving field, I_r the rotor current, and $\cos\theta_r$ the power factor of the rotor current.

In the previous formula the product of rotor current and rotor power factor for a given strength of magnetic revolving field is a maximum value when the phase angle between rotor current and rotor induced voltage is 45° lagging, as indicated in figure 14-4, (C). In this case the reactance of the rotor equals the resistance of the rotor circuit, and the rotor power factor is 70.7 percent. This condition of operation is called the PULL-OUT POINT. Beyond this point, the motor speed falls off rapidly with added load, and the motor stalls.

Variations in applied stator voltage affect the motor torque. This applied voltage establishes m.m.f.'s which create the rotating field. The rotating field, in turn, establishes the rotor current. Because rotor torque varies as the product of these factors, the torque of an induction motor varies as the square of the voltage applied to the stator primary winding.

The rotating field also sweeps across the stator winding which produces it. This action induces a counter e.m.f. in the winding. The counter e.m.f. opposes the applied voltage and limits the stator currents. If the applied voltage is increased to magnetic saturation, the counter e.m.f. is limited, and the primary current becomes dangerously high.

SYNCHRONOUS SPEED AND SLIP

The speed, N, of the rotating field is called the SYNCHRONOUS SPEED of the motor. As previously stated, the torque on the rotor tends to turn the rotor in the same direction as the revolving field. If the motor is not driving a load, it will accelerate to nearly the same speed as the revolving field. During the starting period, the increase in rotor speed is accompanied by a decrease in induced rotor voltage because the relative motion between the rotating field and rotor conductors is less. If it were possible for the rotor to attain synchronous speed there would be no relative motion between the rotor and the rotating field. There would then be no induced e.m.f. in the rotor, no rotor current, and thus no torque.

It is obvious that an induction motor cannot run at exactly synchronous speed. Instead, the rotor always runs just enough below synchronous speed at no load to establish sufficient rotor current to produce a torque equal to the resisting torque that is caused by the rotor losses.

The frequency of the alternating voltage induced in the rotor depends on the speed of the revolving field with respect to the rotor. One cycle of alternating voltage is induced in the rotor when the stator field sweeps completely around the rotor once. The rotor frequency, f_r, is directly proportional to the percent slip—

$$f_r = \frac{Sf_s}{100}$$

where S is the percent slip and f_s is the frequency of the supply. For example, if the frequency of the supply is 60 cycles per second and the slip is 5 percent, the rotor frequency will be $\frac{5 \times 60}{100} = 3$ cycles per second. The frequency and magnitude of the induced rotor voltage decrease as the rotor speed increases. Both the rotor voltage and frequency would become zero if the rotor could attain synchronous speed.

LOSSES AND EFFICIENCY

The losses of an induction motor include (1) stator copper loss, $I_s^2R_s$, and rotor copper loss, $I_r^2R_r$; (2) stator and rotor core loss; and (3) friction and windage loss. For all practical purposes, the core, bearing friction, and windage losses are considered to be constant for all loads of an induction motor having a small slip. The power output may be measured on a mechanical brake or calculated from a knowledge of the input and the losses. The efficiency is equal to the ratio of the output power to input power; and at full load, it varies from about 85 percent for small motors to more than 90 percent for large motors.

CHARACTERISTICS OF THE CAGE-ROTOR MOTOR

As stated previously, the cage-rotor induction motor is comparable to a transformer with a rotating secondary. At no load, the magnetic revolving field produced by the primary stator winding cuts the turns of the stator winding. This action generates a counter e.m.f. in the stator winding, which limits the line current to a small value. This no-load value is called EXCITING CURRENT. Its function is to maintain the revolving field. Because the circuit is highly inductive, the power factor of the motor with no load is very poor. It may be as much as 30 percent lagging. Because there is no drag on the rotor, it runs at almost synchronous speed and the rotor current is quite small. Hence, the reaction of the rotor m.m.f. on the primary revolving field is small.

When load is added to the motor, the rotor slows down slightly; but the rotating field continues at synchronous speed. Therefore, the rotor current and slip increase. The motor torque increases more than the decrease in speed and the power output increases. The increased rotor m.m.f. opposes the primary field flux and lowers it slightly. The primary counter e.m.f. therefore decreases slightly and primary current increases. The load component of primary current maintains the rotating field and prevents its further weakening because of the rotor-current opposition. Because of the relatively low internal impedance of the motor windings, a small reduction in speed and counter e.m.f. in the primary may be accompanied by large increases in motor current, torque, and power output. Thus, the cage-rotor motor has essentially constant-speed variable-torque characteristics.

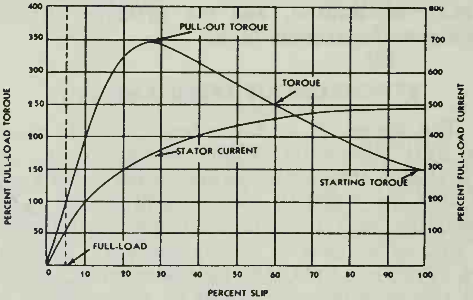
If the induction motor is stalled by overload, the resulting increased rotor current lowers the primary counter e.m.f. and causes excessive primary current. This excessive current may damage the motor winding. When the rotor of an induction motor is locked, the voltage applied to the primary winding should not exceed 50 percent of its rated voltage.

When the motor is operating at full load, the load component of stator current is more nearly in phase with the voltage across each stator phase because of the mechanical output (true power component) of the motor. The power factor is considerably improved over the no-load condition.

The torque and current curves for a 3-phase induction motor with cage rotor are shown in figure 14-5 (A). Rotor reactance increases with slip and increasingly affects the rotor current and power factor as the motor load is increased. The pull-out point on the torque curve occurs at about 25 percent slip. Maximum torque at this condition is about 3.5 times the normal full-load value, and, as previously mentioned, corresponds to a rotor power factor of 70.7 percent. Thus, for the pull-out condition, the rotor resistance equals the rotor reactance and the rotor power factor angle equals 45°. Any additional load on the motor beyond this point causes the rotor to pull out of its normal speed range and to stall quickly. At standstill, stator current is nearly 5 times normal; hence, constant-potential motor circuits like the one supplying this motor are equipped with time-delay automatic-overload protective devices. Sustained overload causes a circuit breaker to open and to protect both the motor and the circuit from damage.

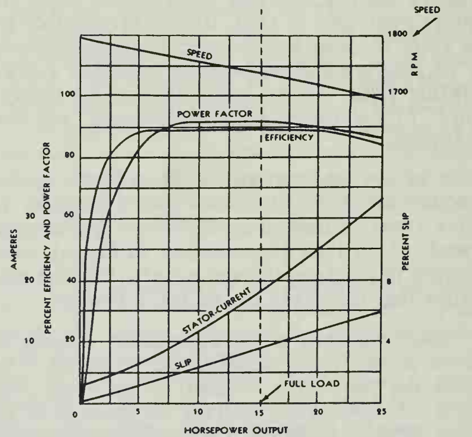
The performance curves of a 4-pole 3-phase 450-volt 15-horsepower cage-rotor motor are shown in figure 14-5 (B). The full-load slip is only about 3.5 percent. At standstill, the rotor reactance of this type of motor is nearly 5 times as great as the rotor resistance. At full load, however, the rotor reactance is much less than the rotor resistance. When the motor is running, the rotor current is determined principally by the rotor resistance. The torque increases up to the pull-out point as the slip increases. Beyond this point the torque decreases and the motor stalls. Because the change in speed from no load to full load is relatively small, the motor torque and the horsepower output are considered to be directly proportional.

The cage-rotor induction motor has a fixed rotor circuit. The resistance and inductance of the windings are determined when the motor is designed and cannot be changed after it is built. The standard cage-rotor motor is a general-purpose motor. It is used to drive loads that



TORQUE AND CURRENT CURVES

(A)



PERFORMANCE CURVES FOR 4-POLE 3-PHASE 450-VOLT 15-HP CAGE-ROTOR MOTOR

(B)

Figure 14-5.—Characteristic curves of a cage-rotor motor.

require a variable torque at approximately constant speed with high full-load efficiency—such as blowers, centrifugal pumps, motor-generator sets, and various machine tools.

If the load requires special operating characteristics, such as high-starting torque, the cage rotor is designed to have high resistance. The starting current of a motor with a high-resistance rotor is less than that of a motor with a low-resistance rotor. The high-resistance rotor motor, like the cumulative compounded d-c motor, has wider speed variations than the low-resistance rotor motor. The high rotor resistance also increases the rotor copper losses, resulting in a lower efficiency than that of the low resistance type. These motors are used to drive cranes and elevators when high-starting torque and moderate-starting current are required and when it is desired to slow down the motor without drawing excessive currents.

CHARACTERISTICS OF WOUND-ROTOR MOTOR

The wound-rotor, or slipring, induction motor is used when it is necessary to vary the rotor resistance in order to limit the starting current or to vary the motor speed. As previously explained, the starting torque may be made equal to the pull-out torque by increasing the rotor resistance to the point where it equals the rotor reactance at standstill. Maximum torque at start can be obtained with a wound-rotor motor with about 1.15 times full-load current; whereas a cage-rotor motor may require 5 times full-load current to produce maximum torque at start. Because the rotor-circuit copper losses are largely external to the rotor winding, the wound-rotor motor is desirable for an application which requires frequent starts.

The advantages of the wound-rotor induction motor over the cage-rotor induction motor are: (1) high-starting torque with moderate starting current, (2) smooth acceleration under heavy loads, (3) no excessive heating during starting, (4) good running characteristics, and (5) adjustable speed. The chief disadvantage of the wound-rotor is that the initial and maintenance costs are greater than those of the cage-rotor motor.

Synchronous Motors

The synchronous motor differs from the induction motor in several ways. The synchronous motor requires a separate source of d-c for the field. It also requires special starting components. These include a salient-pole field with starting grid winding. The rotor of the conventional type synchronous motor is essentially the same as that of the salient-pole a-c generator. The stator windings of induction and synchronous motors are essentially the same. The stator of a synchronous motor is illustrated in figure 14-6 (A).

If supplied with proper voltage, a d-c generator operates satisfactorily as a d-c motor, and there is practically no difference in construction and rating between the two. Similarly, an a-c generator becomes à synchronous motor if electric power is supplied to its terminals from an external source. Synchronous-motor rotating fields are generally of the salient-pole type, as shown in figure 14-6 (B).

Assume, for example, that two a-c generators of the salient-pole type are operating in parallel and feeding the same bus. If the prime mover is disconnected from one of the generators, it will become a synchronous motor and continue to run at the same speed, drawing its power from the other a-c generator.

With the exception of certain modifications to make its operation more efficient and also to make it self-starting, the synchronous motor is very similar to the salient-pole rotating-field a-c generator. The rotor fields of both are separately excited from a d-c source, and both run at synchronous speeds under varying load conditions. An 8-pole generator rotor revolving at 900 r.p.m. generates 60 cycles per second; likewise, an 8-pole synchronous motor supplied with 60-cycle current will rotate at 900 r.p.m.

PRINCIPLE OF OPERATION

A polyphase current is supplied to the stator winding of a synchronous motor and produces a rotating magnetic field the same as in an induction motor. A direct current is supplied to the rotor winding, thus producing a fixed polarity at each pole. If it could be assumed that the rotor had no inertia and that no load of any kind were applied, then the rotor would revolve in step with the revolving field as soon as power was applied to both of the windings. This, however,

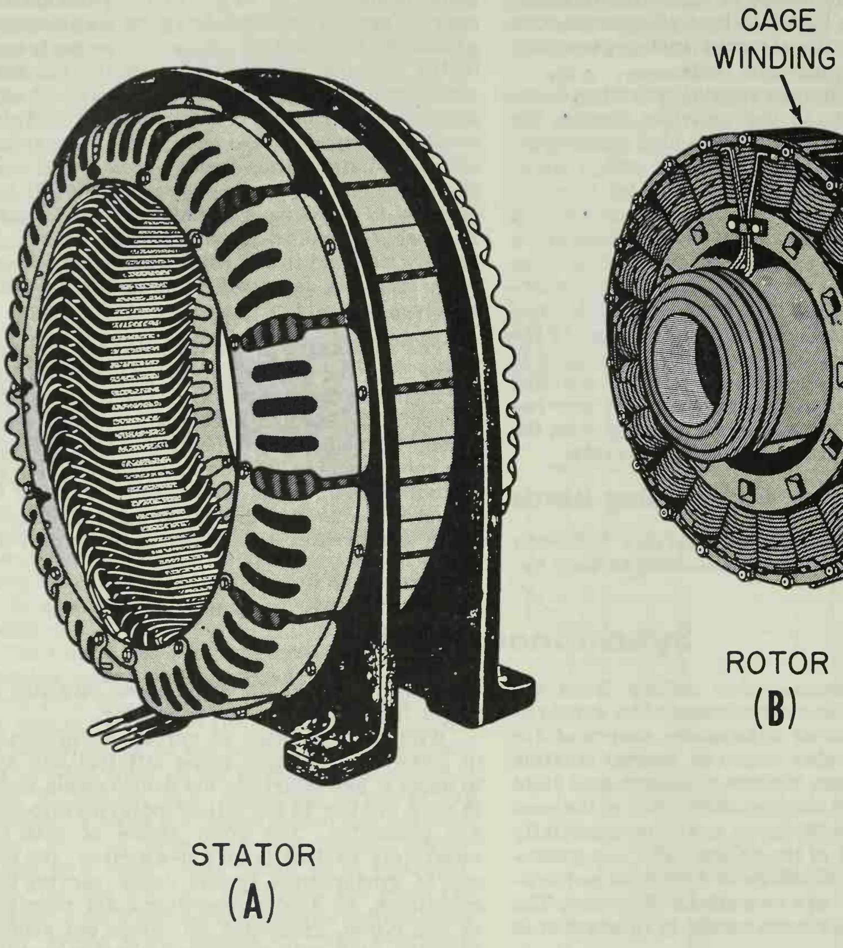


Figure 14-6.—Synchronous motor.

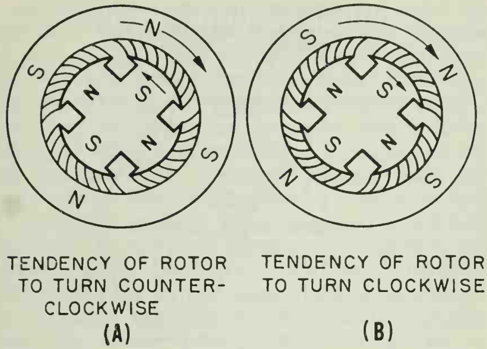
is not the case. The rotor has inertia, and in addition there is a load.

The reason a synchronous motor has to be brought up to synchronous speed by special means, may be understood from a consideration of figure 14-7.

If the stator and rotor windings are energized, then as the poles of the rotating magnetic field approach rotor poles of opposite polarity (fig. 14-7 (A), the attracting force tends to turn the rotor in the direction opposite to that of the rotating field. As the rotor starts in this direction, the rotating-field poles are leaving the rotor poles (fig. 14-7 (B)), and this tends to pull the rotor poles in the same direction as the rotating field. Thus, the rotating field tends to pull the rotor poles first in one direction and then in the other, with the result that the starting torque is zero.

STARTING

As has been explained, some type of starter must be used with the synchronous motor to bring the rotor up to synchronous speed. Although a small induction motor may be used to bring the rotor up to speed, this is not generally done.


N
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TENDENCY OF ROTOR TO TURN COUNTER-CLOCKWISE
(A)
TENDENCY OF ROTOR TO TURN CLOCKWISE
(B)

Figure 14-7.—Operating principle of synchronous motor.

Sometimes, if direct current is available, a d-c motor coupled to the rotor shaft may be used to bring the rotor up to synchronous speed. After synchronous speed is attained, the d-c motor is converted to operate as a generator to supply the necessary direct current to the rotor of the synchronous motor.

In general, however, another method is used to start the synchronous motor. A cage-rotor winding is placed on the rotor of the synchronous motor to make the machine self-starting as an induction motor. At start, the d-c rotor field is deenergized and a reduced polyphase voltage is applied to the stator windings. Thus, the motor starts as an induction motor and comes up to a speed which is slightly less than synchronous speed. The rotor is then excited from the d-c supply (generally a d-c generator mounted on the shaft) and the field rheostat adjusted for minimum line current.

If the armature has the correct polarity at the instant synchronization is reached, the stator current will decrease when the excitation voltage is applied. If the armature has the incorrect polarity, the stator current will increase when the excitation voltage is applied. This is a transient condition, and if the excitation voltage is increased further the motor will slip a pole and then come into step with the revolving field of the stator.

If the rotor d-c field winding of the synchronous machine is open when the stator is energized, a high a-c voltage will be induced in it because the rotating field sweeps through the large number of turns at synchronous speed. It is therefore necessary to connect a resistor of low resistance across the rotor d-c field winding during the starting period. During the starting period, the d-c field winding is disconnected from the source and the resistor is connected across the field terminals. This permits alternating current to flow in the d-c field winding. Because the impedance of this winding is high compared with the inserted external resistance, the internal voltage drop limits the terminal voltage to a safe value.

STARTING TORQUE

Both the alternating currents induced in the rotor field winding and the cage-rotor winding during starting are effective in producing the starting torque. The torques produced by the rotor d-c field winding and the cage-rotor winding at different speeds are shown by the curves T_r and T_s, respectively, of figure 14-8. Curve T is the sum of T_r and T_s and indicates the total torque at different speeds during the starting period. Note that T_r is very effective in producing torque as the rotor approaches synchronous speed, but that both windings contribute no torque at synchronous speed because the induced voltage is zero and no d-c excitation is yet applied to the d-c winding.

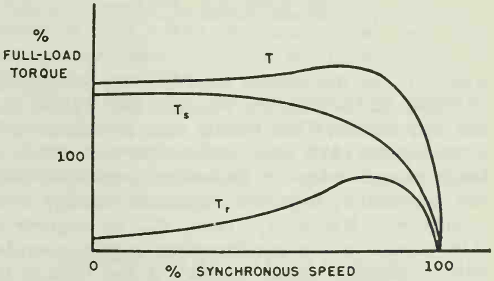
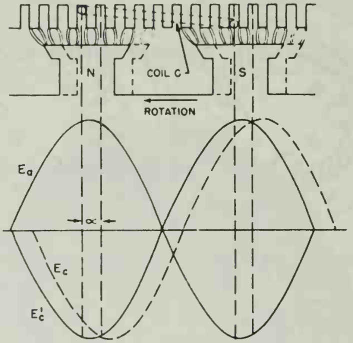


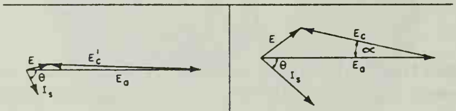
Figure 14-8.—Starting torque of a synchronous motor.

EFFECT OF VARYING LOAD AND FIELD STRENGTH

The power factor of an induction motor depends on the load and varies with it. The power factor of a synchronous motor carrying a definite load may be unity or less than unity, either lagging or leading, depending on the d-c field strength.

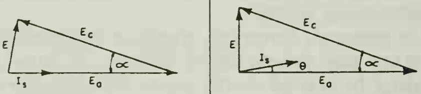


(A) WAVEFORMS



(B) NO-LOAD VECTORS

(C) LAGGING CURRENT



(D) UNITY POWER FACTOR

(E) LEADING CURRENT

Figure 14-9.-Effect of varying the load and field strength of a synchronous motor.

The induced (counter) e.m.f. in armature coil *C*, shown in figure 14-9 (A), is maximum when its sides are opposite the pole centers and minimum when its sides are midway between the pole tips; and it varies as indicated by the solid-line curve, E'_c. When the motor carries no load, the counter voltage E'_c is practically 180° out of phase with the applied voltage E_a (fig 14-9 (A) and (B)). If the field is adjusted so that E_c almost equals E_a, the stator current I_s is small and corresponds to the exciting current in a transformer.

When load is applied to the motor it causes the poles to be pulled α degrees behind their no-load position, as indicated by the broken curve in figure 14-9 (A), and the counter e.m.f. occurs α degrees later. This is indicated by curve E_c in figure 14-9 (A), and by vector E_c in figure 14-9(C). The resultant voltage, *E*, causes the stator current I_s, to lag behind E_a by angle θ .

In a d-c motor the armature current is determined from the equation

$$I_a = \frac{E_a - E_c}{R_a}.$$

Similarly, in a synchronous motor the stator current is determined as

$$I_s = \frac{\text{vector sum of } E_a \text{ and } E_c}{Z_s},$$

where I_s is the stator current, E_a the applied voltage, E_c the counter voltage, and Z_s the stator impedance. This vector sum is indicated by *E* in figure 14-9 (C). The stator reactance is large compared to its resistance, and therefore the current I_s lags the resultant voltage *E* by nearly 90°. Hence, I_s, lags, E_a, by angle θ. In this condition the synchronous motor operates with a lagging power factor. If the load is increased, the rotor poles are pulled further behind the stator poles, which causes E_c to lag further, and angle α to increase. This action causes the resultant voltage, *E*, and stator current, I_s, to increase.

Because the speed is constant, if the field excitation is decreased, the counter voltage, E_c, decreases; and the resultant voltage, *E*, becomes greater. The stator current becomes greater and lags the applied voltage, E_a, a greater amount. On the other hand, if the field excitation is increased until the current, I_s, is in phase with the applied voltage, E_a, the power factor of the motor becomes unity for a given load (fig. 14-9 (D)). For a definite load at unity power factor, *E* and I_s are both at their minimum. If the field excitation is further increased, I_s increases and leads E_a (fig. 14-9 (E)). Thus, for a definite load, the power factor is governed by the field excitation—that is, a weak field produces lagging current and a strong field produces a leading current. Normal field excitation for a given load occurs when I_s is in phase with E_a.

The so-called synchronous motor **V** curves, which indicate the variations of current for a constant load and varied field excitation, are shown in figure 14-10. The corresponding variations of power factor are shown also.

Although synchronous motors are used as propulsion motors in practically all Navy vessels that have a-c electric propulsion systems, they have very few other uses in the Navy. However, a synchronous motor is frequently used in shore-based systems to change the power factor of the system to which it is paralleled by adjusting its field excitation. If operated without load, its power factor may be adjusted to a value as low as 10 percent leading. When operated under this condition, the motor is generally referred to as a synchronous condenser because it takes a leading current in the same manner as capacitors. In this case the synchronous condenser takes only enough true power from the line to supply its losses. At the same time, it supplies a high leading reactive power, which cancels the lagging reactive power taken by the parallel inductive loads, and the system power factor is thereby improved.

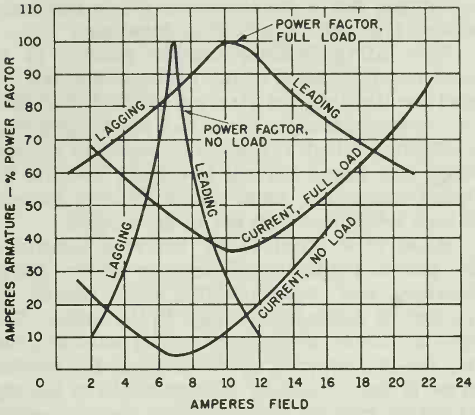


Figure 14-10.—V curves for a synchronous motor of 15 kv.-a.

Alternating-Current Motor Starters

As in the case of d-c motors, some type of starter (controller) may also be employed on a-c motors to limit the initial inrush of current.

ACROSS-THE-LINE starters are the most common form aboard ship because of their simplicity and because ships are generally equipped with sufficient generating capacity to handle the high starting currents of the motors. This type of starter throws the stator winding of the motor directly across the main supply line. This may be feasible if the motor is not too large (5 horsepower or less) and if the generating capacity of the a-c generator can take care of the added load.

PRIMARY RESISTOR starters insert a resistor in the PRIMARY circuit (the stator circuit) of the motor for starting, or for starting and speed control. This starter is used when it is necessary to limit the starting current of a large a-c motor so as not to put too great a load on the system. If the resistor is used only during starting, its rating is based on intermittent operation, in which case it is relatively small and operates at a higher temperature. If the resistor is used also for speed control of small motors, such as for ventilating fans, its rating is based on continuous operation. In this case the resistor is relatively large and operates at a lower temperature.

SECONDARY RESISTOR starters insert a resistor in the secondary circuit (the rotor circuit of the form-wound type of induction motor) for starting and speed control. This starter may be used to limit starting currents, but is usually found where speed control of a large a-c motor is required, in which case the resistors are rated for continuous duty. Examples are some elevators and hoists equipped with direct a-c electric drives.

COMPENSATOR, or AUTOTRANSFORMER, starters start the motor at reduced voltage through an autotransformer, and subsequently connect the motor to full voltage after acceleration. The compensator may be either of two types.

1. The OPEN-TRANSITION type, during the transition period of shifting the motor from the autotransformer to direct connection with the supply lines, disconnects the motor from all power for a short period of time during which, if the motor is of the synchronous type, it may coast and slip out of phase with the power supply. When the motor is then connected directly to the power lines, a high transition current may result.

2. The CLOSED-TRANSITION type keeps the motor connected to the power supply at all times during the transition period, thus not

permitting the motor to decelerate. Accordingly, no high transition current is developed.

The AUTOTRANSFORMER starter is the most common form of the reduced-voltage type used for limiting the starting current of a motor. The open-transition form has the disadvantage of allowing a high transition current to develop, which can cause circuit breakers to open. The closed-transition form is preferable because no high transition current is developed.

REACTOR STARTERS insert a reactor in the primary circuit of an a-c motor during starting, and subsequently short-circuit the reactor to apply full voltage to the motor. This type of starter is not very widely used at present, but is becoming more common for starting large motors because it does not have the high transition current problem of the open-transition compensator and is smaller than the closed-transition compensator.

A simplified schematic diagram of a compensator, or autotransformer, starter is shown in figure 14-11. Assume that the line voltage is 100 volts and that when the taps on the autotransformer are positioned as shown (in the starting position) 40 volts will be applied to the 3-phase motor stator. With the reduction in motor voltage, there is a corresponding reduction in starting current drawn from the line. At the same time, the motor current supplied by the secondary low-voltage windings is proportionately increased by the transformer action.

After the proper time interval, during which acceleration occurs, full-line voltage is applied to the motor.

A resistance starter could be used in place of autotransformer to lower the voltage applied to the stator. The power factor would be improved, but the line current would be greater. The autotransformer has the advantage in permitting the motor to draw a relatively large starting current from the secondary with a relatively low line current.

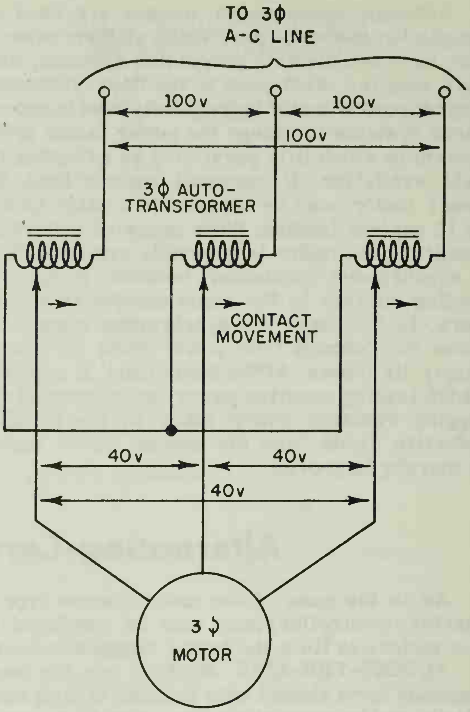


Figure 14-11.—Simplified schematic diagram of autotransformer starter.

Single-Phase Motors

Single-phase motors, as their name implies, operate on a single-phase power supply. These motors are used extensively in fractional horsepower sizes in the Navy and in commercial and domestic applications. The advantages of using single-phase motors in small sizes are that they are less expensive to manufacture than other types, and they eliminate the need for 3-phase a-c lines. Single-phase motors are used in interior communications equipment, fans, refrigerators, portable drills, grinders, and so forth.

A single-phase induction motor with only one stator winding and a cage rotor is like a 3-phase induction motor with a cage rotor except that the single-phase motor has no magnetic revolving field at start and hence no starting torque. However, if the rotor is brought up to speed by external means, the induced currents in the rotor will cooperate with the stator currents to produce a revolving field, which causes the rotor to continue to run in the direction in which it was started.

Several methods are used to provide the single-phase induction motor with starting torque. These methods identify the motor as split phase, capacitor, shaded pole, repulsion, and so forth.

Another class of single-phase motors is the a-c series (universal) type. Only the more commonly used types of single-phase motors are described. These include the (1) split-phase motor, (2) capacitor motor, (3) shaded-pole motor, (4) repulsion-start motor, and (5) a-c series motor.

SPLIT-PHASE MOTOR

The split-phase motor (fig. 14-12 (A)), has a stator composed of slotted laminations that contain an auxiliary (starting) winding and a running (main) winding. The axes of these two windings are displaced by an angle of 90 electrical degrees. The starting winding has fewer turns and smaller wire than the running winding, hence has higher resistance and less reactance. The main winding occupies the lower half of the slots and the starting winding occupies the upper half. The two windings are connected in parallel across the single-phase line supplying the motor. The motor derives its name from the action of the stator during the starting period. The single-phase stator is split into two windings (phases), which are displaced in space by 90°, and which contain currents displaced in time phase by an angle of approximately 15° (fig. 14-12 (B)). The current, I_s, in the starting winding lags the line voltage by about 30° and is less than the current in the main winding because of the higher impedance of the starting winding. The current, I_m, in the main winding lags the applied voltage by about 45°. The total current, I_{line}, during the starting period is the vector sum of I_s and I_m.

At start, these two windings produce a magnetic revolving field that rotates around the stator air gap at synchronous speed. As the rotating field moves around the air gap, it cuts across the rotor conductors and induces a voltage in them, which is maximum in the area of highest field intensity and therefore is in phase with the stator field. The rotor current lags the rotor voltage at start by an angle that approaches 90° because of the high rotor reactance. The interaction of the rotor currents and the stator field cause the rotor to accelerate in the direction in which the stator field is rotating. During acceleration, the rotor voltage, current, and reactance are reduced and the rotor currents come closer to an in-phase relation with the stator field.

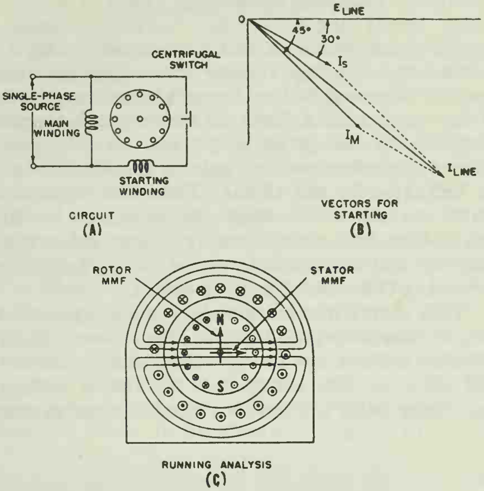


Figure 14-12.—Split-phase motor.

When the rotor has come up to about 75 percent of synchronous speed, a centrifugally operated switch disconnects the starting winding from the line supply, and the motor continues to run on the main winding alone. Thereafter, the rotating field is maintained by the interaction of the rotor magnetomotive force and the stator magnetomotive force. These two m.m.f.'s are pictured as the vertical and horizontal vectors respectively in the schematic diagram of figure 14-12 (C).

The stator field is assumed to be rotating at synchronous speed in a clockwise direction, and the stator currents correspond to the instant that the field is horizontal and extending from left to right across the air gap. The left-hand rule for magnetic polarity of the stator indicates that the stator currents will produce an *N* pole on the left side of the stator and an *S* pole on the right side. The motor indicated in the figure is wound for two poles.

Applying the left-hand rule for induced voltage in the rotor (the thumb points in the direction of motion of the conductor with respect to the field), the direction of induced voltage is back on the left side of the rotor and forward on the right side. The rotor voltage causes a rotor current to flow, which lags the rotor voltage by an angle whose tangent is the ratio of rotor reactance to rotor resistance. This is a relatively small angle because the slip is small. Applying the left-hand rule for magnetic polarity to the rotor winding, the vertical vector pointing upward represents the direction and magnitude of the rotor m.m.f. This direction indicates the tendency to establish an *N* pole on the upper side of the rotor and an *S* pole on the lower side, as indicated in the figure. Thus, the rotor and stator m.m.f.'s are displaced in space by 90° and in time by an angle that is considerably less than 90°, but sufficient to maintain the magnetic revolving field and the rotor speed.

This motor has the constant-speed variable-torque characteristics of the shunt motor. Many of these motors are designed to operate on either 110 volts or 220 volts. For the lower voltage the stator coils are divided into two equal groups and these are connected in parallel. For the higher voltage the groups are connected in series. The starting torque is 150 to 200 percent of the full-load torque and the starting current is 6 to 8 times the full-load current. Fractional-horsepower split-phase motors are used in a variety of equipments such as washers, oil burners, and ventilating fans. The direction of rotation of the split-phase motor can be reversed by interchanging the starting winding leads.

CAPACITOR MOTOR

The capacitor motor is a modified form of split-phase motor, having a capacitor in series with the starting winding. An external view is shown in figure 14-13, with the capacitor located on top of the motor. The capacitor produces a

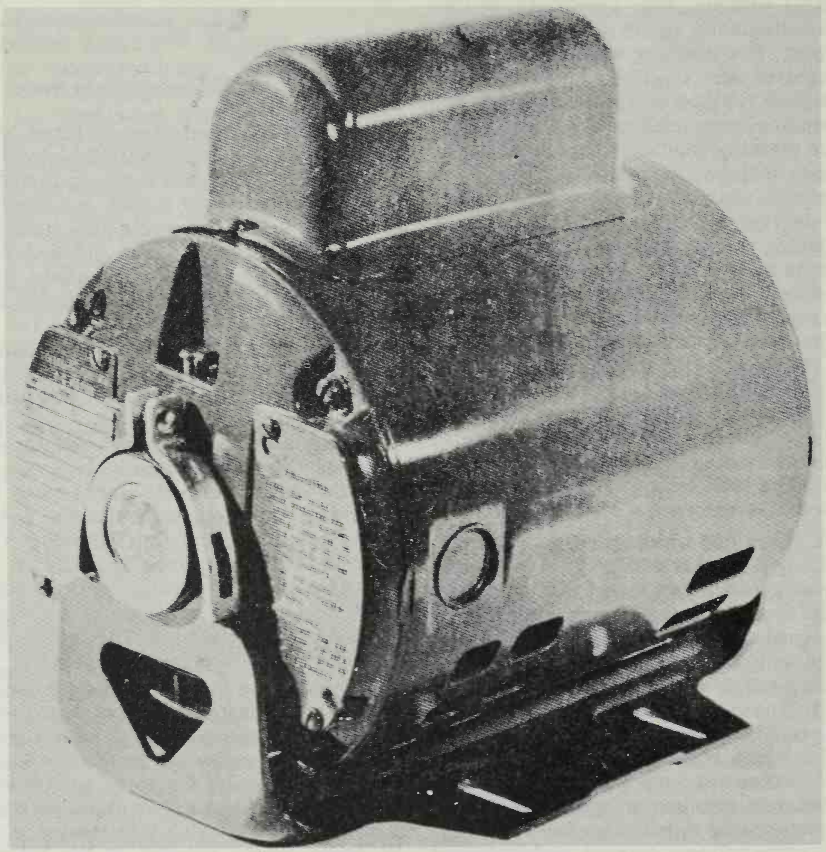


Figure 14-13.—Capacitor motor.

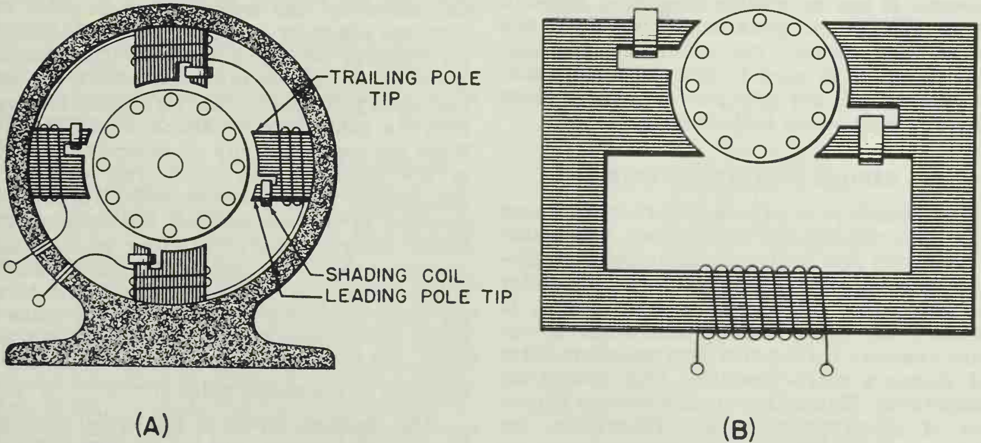
greater phase displacement of currents in the starting and running windings than is produced in the split-phase motor. The starting winding is made of many more turns of larger wire and is connected in series with the capacitor. The starting winding current is displaced approximately 90° from the running winding current. Since the axes of the two windings are also displaced by an angle of 90°, these conditions produce a higher starting torque than that of the split-phase motor. The starting torque of the capacitor motor may be as much as 350 percent of the full-load torque.

If the starting winding is cut out after the motor has increased in speed, the motor is called a CAPACITOR-START MOTOR. If the starting winding and capacitor are designed to be left in the circuit continuously, the motor is called a CAPACITOR MOTOR. Electrolytic capacitors for capacitor-start motors vary in size from about 80 microfarads for 1/8-horsepower motors to 400 microfarads for one-horsepower motors. Capacitor motors of both types are made in sizes ranging from small fractional horsepower motors up to about 10 horsepower. They are used to drive grinders, drill presses, refrigerator compressors, and other loads that require relatively high starting torque. The direction of rotation of the capacitor motor may be reversed by interchanging the starting winding leads.

SHADED-POLE MOTOR

The shaded-pole motor employs a salient-pole stator and a cage rotor. The projecting poles on the stator resemble those of d-c machines except that the entire magnetic circuit is laminated and a portion of each pole is split to accommodate a short-circuited copper strap called a SHADING COIL (fig. 14-14)). This motor is generally manufactured in very small sizes, up to 1/20 horsepower. A 4-pole motor of this type is illustrated in figure 14-14 (A). The shading coils are placed around the leading pole tip and the main pole winding is concentrated and wound around the entire pole. The 4 coils comprising the main winding are connected in series across the motor terminals. An inexpensive type of 2-pole motor employing shading coils is illustrated in figure 14-14 (B).

During that part of the cycle when the main pole flux is increasing, the shading coil is cut by the flux, and the resulting induced e.m.f. and current in the shading coil tend to prevent the flux from rising readily through it. Thus, the greater portion of the flux rises in that portion of the pole that is not in the vicinity of the shading coil. When the flux reaches its maximum value, the rate of change of flux is zero, and the voltage and current in the shading coil also are zero.



(A)
FOUR-POLE MOTOR

(B)
TWO-POLE MOTOR

Figure 14-14.—Shaded-pole motor.

At this time the flux is distributed more uniformly over the entire pole face. Then as the main flux decreases toward zero, the induced voltage and current in the shading coil reverse their polarity, and the resulting magnetomotive force tends to prevent the flux from collapsing through the iron in the region of the shading coil. The result is that the main flux first rises in the unshaded portion of the pole and later in the shaded portion. This action is equivalent to a sweeping movement of the field across the pole face in the direction of the shaded pole. The cage rotor conductors are cut by this moving field and the force exerted on them causes the rotor to turn in the direction of the sweeping field.

Most shaded-pole motors have only one edge of the pole split, and therefore the direction of rotation is not reversible. However, some shaded-pole motors used in fire control and interior communications circuits have both leading and trailing pole tips split to accommodate shading coils. The leading pole tip shading coils form one series group, and the trailing pole tip shading coils form another series group. Only the shading coils in one group are simultaneously active, while those in the other group are on open circuit.

The shaded-pole motor is similar in operating characteristics to the split-phase motor. It has the advantages of simple construction and low cost. It has no sliding electrical contacts and is reliable in operation. However, it has low starting torque, low efficiency, and high noise level. It is used to operate small fans. The shading coil and split pole are used in clock motors to make them self-starting.

REPULSION-START MOTOR

The repulsion-start motor has a form-wound rotor with commutator and brushes. The stator is laminated and contains a distributed single-phase winding. In its simplest form, the stator resembles that of the single-phase motor. In addition, the motor has a centrifugal device which removes the brushes from the commutator and places a short-circuiting ring around the commutator. This action occurs at about 75 percent of synchronous speed. Thereafter, the motor operates with the characteristics of the single-phase induction motor.

The starting torque of the repulsion-start induction motor is developed through the interaction of the rotor currents and the single-phase stator field. Unlike the split-phase motor, the stator field does not rotate at start, but alternates instead. The rotor currents are induced through transformer action. For example, in the 2-pole motor of figure 14-15 (A), the stator currents are shown for the instant when a north pole is established on the upper side of the stator, and a south pole on the lower side. The induced voltage in the rotor causes the rotor currents to flow in such a direction as to oppose the stator field. These currents flow in opposite directions under the left and right portions of the north pole and in similar manner under the south pole. Thus, the net force to turn the rotor is zero when the brushes are located in the positions shown.

In figure 14-15 (B), the brushes are moved 90° from their original positions, and again there is no rotor turning effort because in this case the rotor current is zero. There can be no rotor current in this position because the transformer induced voltages are equal and opposite to each other in the two halves (upper and lower) of the rotor winding.

In figure 14-15 (C), the brush axis is displaced from the stator polar axis by an angle of about 25°, and in this position maximum torque is developed.

The direction of the induced currents in the rotor under the north pole of the stator is toward the observer, and under the south pole, away from the observer. Applying the right-hand rule for motors, the force acting on the conductors under the north pole is toward the left, and under the south pole, toward the right, thus tending to turn the rotor in a counterclockwise direction. When the stator polarity reverses, the direction of the rotor current also reverses, thereby maintaining the same direction of rotation. The function of the commutator and brushes is to divide the rotor currents along an axis that is displaced from the axis of the stator field in a counterclockwise direction. The motor derives its name from the repulsion of like poles between the rotor and stator. Thus, the rotor currents establish the rotor poles $N'-S'$, which are repelled by the stator poles $N-S$.

The starting torque is 250 to 450 percent of the full-load torque, and the starting current is 375 percent of the full-load current. This motor is made in fractional horsepower sizes and in larger sizes up to 15 horsepower, but has been replaced in large parts by the cheaper and more rugged capacitor motor. The repulsion-start motor has higher pull-out torque (torque at which the motor stalls) than the capacitor-start motor, but the capacitor start motor can bring up to full speed loads that the repulsion motor can start but cannot accelerate.

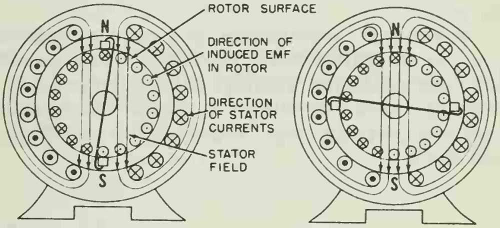
A-C SERIES MOTOR

The a-c series motor will operate on either a-c or d-c circuits. It will be recalled that the direction of rotation of a d-c series motor is independent of the polarity of the applied voltage, provided the field and armature connections remain unchanged. Hence, if a d-c series motor is connected to an a-c source, a torque will be developed which tends to rotate the armature in one direction. However, a d-c series motor does not operate satisfactorily from an a-c supply for the following reasons:

1. The alternating flux sets up large eddy-current and hysteresis losses in the unlaminated portions of the magnetic circuit and causes excessive heating and reduced efficiency.
2. The self-induction of the field and armature windings causes a low power factor.
3. The alternating field flux establishes large currents in the coils that are short-circuited by the brushes; this action causes excessive sparking at the commutator.

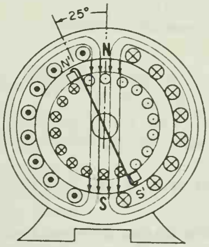
To design a series motor for satisfactory operation on alternating current the following changes are made:

1. The eddy-current losses are reduced by laminating the field poles, yoke, and armature.
2. Hysteresis losses are minimized by using high-permeability transformer-type silicon-steel laminations.
3. The reactance of the field windings is kept satisfactorily low by using shallow pole pieces, few turns of wire, low frequency (usually 25 cycles for large motors), low flux density, and low reluctance (a short air gap).
4. The reactance of the armature is reduced by using a compensating winding embedded in the pole pieces. If the compensating winding is connected in series with the armature (fig. 14-16 (A)), the armature is CONDUCTIVELY compensated. If the compensating winding is short-circuited on itself (fig. 14-16 (B)), the armature is INDUCTIVELY compensated. If the motor is designed for operation on both d-c and a-c circuits, the compensating winding is connected in series with the armature. The axis of the compensating winding is displaced from the main field axis by an angle of 90°. This arrangement is similar to the compensating winding used in some d-c motors and generators to overcome armature reaction. The compensating winding establishes a counter magnetomotive force which neutralizes the effect of the armature magnetomotive force, thereby preventing distortion of the main field flux and reducing the armature reactance. The inductively compensated armature acts like the primary of a transformer, the secondary of which is the shorted compensating winding. The shorted secondary receives an induced voltage by the action of the alternating armature flux, and the resulting current flowing through the turns of the compensating winding establish the opposing magnetomotive force that neutralizes the armature reactance.


ROTOR SURFACE
DIRECTION OF INDUCED EMF IN ROTOR
DIRECTION OF STATOR CURRENTS
STATOR FIELD
N
S
N
S

MAXIMUM ROTOR CURRENT AND ZERO TORQUE
(A)

ZERO ROTOR CURRENT AND ZERO TORQUE
(B)



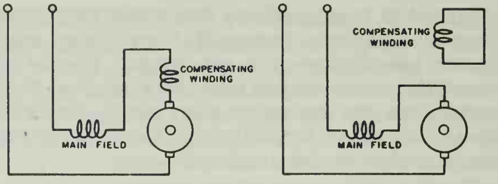
BOTH ROTOR CURRENT AND TORQUE
(C)

Figure 14-15.—Repulsion-start induction motor.

5. Sparking at the commutator is reduced by the use of PREVENTIVE LEADS P_1, P_2, P_3, and so forth (fig. 14-16 (C)). A ring armature is shown for simplicity. When coils at *A* and *B* are shorted by the brushes, the induced current is limited by the relatively high resistance of the leads. Preventive leads are used in some of the older type a-c series motors on electric locomotives. Sparking at the brushes is also reduced by using armature coils having only a single turn and multipolar fields. High torque is obtained by having a large number of armature conductors and a large-diameter armature. Thus, the commutator has a large number of commutator bars that are very thin, so that the armature voltage is limited to about 250 volts.

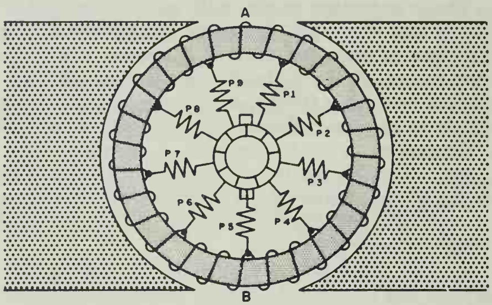
The operating characteristics of the a-c series motor are similar to those of the d-c series motor. The speed will increase to a dangerously high value if the load is removed from the motor.

Fractional horsepower a-c series motors are called UNIVERSAL MOTORS. They do not have compensating windings or preventive leads. They are used extensively in the Navy to operate fans and portable tools, such as drills, grinders, and saws.



(A) CONDUCTIVELY COMPENSATED

(B) INDUCTIVELY COMPENSATED



(C) PREVENTIVE COILS

Figure 14-16.-A-c series motor.

QUIZ

1. The variable resistance placed in the rotor circuit of the form-wound rotor is for the purpose of
   a. speed control
   b. frequency control
   c. voltage control
   d. starting torque control

2. The most common method of starting a synchronous motor is
   a. with a separate d-c motor
   b. with a cage-rotor winding
   c. manually
   d. by applying d. c. to the rotor

3. Why does the capacitor motor have a higher starting torque than a split-phase motor? It has
   a. a higher power factor
   b. no displacement between start and main winding currents
   c. less displacement between start and main winding currents
   d. greater displacement between its start and main winding currents

4. The synchronous speed of an induction motor is the
   a. speed at which the rotor turns
   b. speed of the rotating field
   c. frequency of the rotor current
   d. slip in percent of rotor r.p.m.

5. Near synchronous speed, the
   a. voltage induced into the rotor is very small
   b. voltate induced into the rotor is large
   c. applied voltage on the stator is zero
   d. rotor frequency is maximum

6. What circumstances cause a lagging power factor?
   a. I_s lags resultant E by 90° - I_s lags E_a by angle θ
   b. I_s leads resultant E by 90° - I_s leads E_s by angle θ
   c. resultant E lags I_s by 90° - I_s lags E_a by angle ϕ
   d. E_c leads I_s by 90° - I_s leads E_a by angle ϕ

7. What is the direction of rotation of the shaded-pole motor in respect to the sweeping field?
   a. With the sweeping field
   b. Against the sweeping field
   c. Toward the unshaded tip
   d. Depends on direction motor was started
8. Increasing the number of poles in an induction motor
   a. increases the field speed
   b. decreases the field speed
   c. decreases the motor's rated torque
   d. causes the frequency of line E to drop
9. The rotor voltage is proportional to the
   a. strength of the magnetic field
   b. number of conductors on the stator
   c. angle at which lines of force are cut
   d. difference in rotor speed and the speed of the rotating field
10. The most common type of starter used on board ship for a-c motors is the
    a. autotransformer
    b. secondary capacitor
    c. primary resistor
    d. across-the-line
11. In the repulsion induction motor, what is the position of the brushes in relation to the stator polar axis for maximum torque?
    a. 15°
    b. 25°
    c. 45°
    d. 90°
12. Increasing the frequency of the voltage applied to an induction motor causes the
    a. field speed to decrease
    b. field speed to increase
    c. rotor torque to decrease
    d. stator current to increase
13. The purpose of the iron rotor core is to
    a. decrease motor weight
    b. produce eddy currents
    c. reduce air gap reluctance
    d. decrease permeability
14. The frequency of rotor current varies directly with
    a. applied voltage
    b. the resistance of the rotor
    c. the slip
    d. the number of windings on the stator
15. The efficiency of a motor is equal to the
    a. torque output at synchronous speed
    b. amount of current in the rotor
    c. horsepower of the motor
    d. ratio of its output power to its input power
16. The type of starter used when it is necessary to limit the starting current of an a-c motor is the
    a. autotransformer
    b. secondary resistor
    c. primary resistor
    d. primary capacitor
17. The type of starter used for speed control of an a-c motor is the
    a. secondary resistor
    b. open transition
    c. closed transition
    d. primary resistor
18. Motor action is best analyzed by applying
    a. Fleming's right-hand rule
    b. the magnetic laws of polarity
    c. Lenz's law for self-induced voltage
    d. the left-hand motor rule
19. A synchronous motor is not self-starting due to
    a. its lack of a rotating magnetic field
    b. inertia of the rotor
    c. magnetic locking action between rotor and stator fields
    d. its low power factor
20. The single-phase a-c motor is not self-starting because there is
    a. inertia in the rotor
    b. no high starting torque
    c. no revolving magnetic field
    d. a magnetic lock between the rotor and stator
21. In the a-c series motor, how are hysteresis losses minimized? By use of
    a. high frequency voltage
    b. laminations only
    c. hard iron
    d. silicone steel
22. The direction of rotation of an induction motor is
    a. opposite the rotating field direction
    b. same as direction of rotating field
    c. determined by the number of poles
    d. determined by the location of its brushes
23. A synchronous motor differs from an induction motor in that it
    a. is not self-starting
    b. requires an a-c and a d-c power supply
    c. may be used for power factor correction
    d. all of the above
24. How can the direction of rotation of a split-phase induction motor be reversed?
    a. Reverse leads of main winding
    b. Reverse leads of start windings
    c. Reverse leads of one phase
    d. Reverse any two leads
25. Fractional horsepower a-c series motors are called
    a. induction motors
    b. synchronous motors
    c. universal motors
    d. shaded-pole motors

CHAPTER 15

DIRECT-CURRENT GENERATORS

Generators can be designed to supply small amounts of power or they can be designed to supply many thousands of kilowatts of power. Also, generators may be designed to supply either direct current or alternating current. Direct-current generators are described in this chapter. Alternating-current generators were described in chapter 13.

A d-c generator is a rotating machine that converts mechanical energy into electrical energy. This conversion is accomplished by rotating an armature, which carries conductors, in a magnetic field, thus inducing an e.m.f. in the conductors. As stated before, in order for an e.m.f. to be induced in the conductors, a relative motion must always exist between the conductors and the magnetic field in such a manner that the conductors cut through the field. In most d-c generators the armature is the rotating member and the field is the stationary member. A mechanical force is applied to the shaft of the rotating member to cause the relative motion. Thus, when mechanical energy is put into the machine in the form of a mechanical force or twist on the shaft, causing the shaft to turn at a certain speed, electrical energy in the form of voltage and current is delivered to the external load circuit.

It should be understood that mechanical power must be applied to the shaft constantly so long as the generator is supplying electrical energy to the external load circuit.

The power source used to turn the armature is commonly called a PRIME MOVER. Many forms of prime movers are in use, such as steam turbines, diesel engines, gasoline engines, and steam engines. However, in the Navy, the principal sources of power aboard ship are steam turbines and diesel engines. Also, auxiliary power units containing d-c generators driven by gasoline engines are widely used in naval maintenance operations.

In naval aviation, aircraft engines function as prime movers for both a-c and d-c generating equipment.

A d-c generator consists essentially of (1) a steel frame or yoke containing the pole pieces and field windings, (2) an armature consisting of a group of copper conductors mounted in a slotted cylindrical core, made up of thin steel disks called LAMINATIONS, (3) a commutator for maintaining the current in one direction through the external circuit, and (4) brushes with brush holders to carry the current from the commutator to the external load circuit.

Though both contain the same essential parts, the shipboard d-c generator and the d-c generator used on aircraft are quite different in size, rating, and appearance. A typical generator used aboard ship is shown in figure 15-1 (A); an aircraft generator is shown in part (B). Shipboard generators may weigh thousands of pounds and be rated in the hundreds of kilowatts. Aircraft generators rarely exceed eighty pounds in weight or nine kilowatts in rating.

Construction

FRAME

The d-c generator field frame, or yoke, is usually made of annealed steel. The use of steel reduces the reluctance of the magnetic circuit to a low value and therefore reduces the necessary size of the field windings. The frame provides a mechanical support for the pole pieces and serves as a portion of the magnetic circuit to provide the necessary flux across the air gap.

The end bells are bolted to the frame structure and support the armature shaft bearings. One end bell also supports the brush rigging and extends over the commutator.

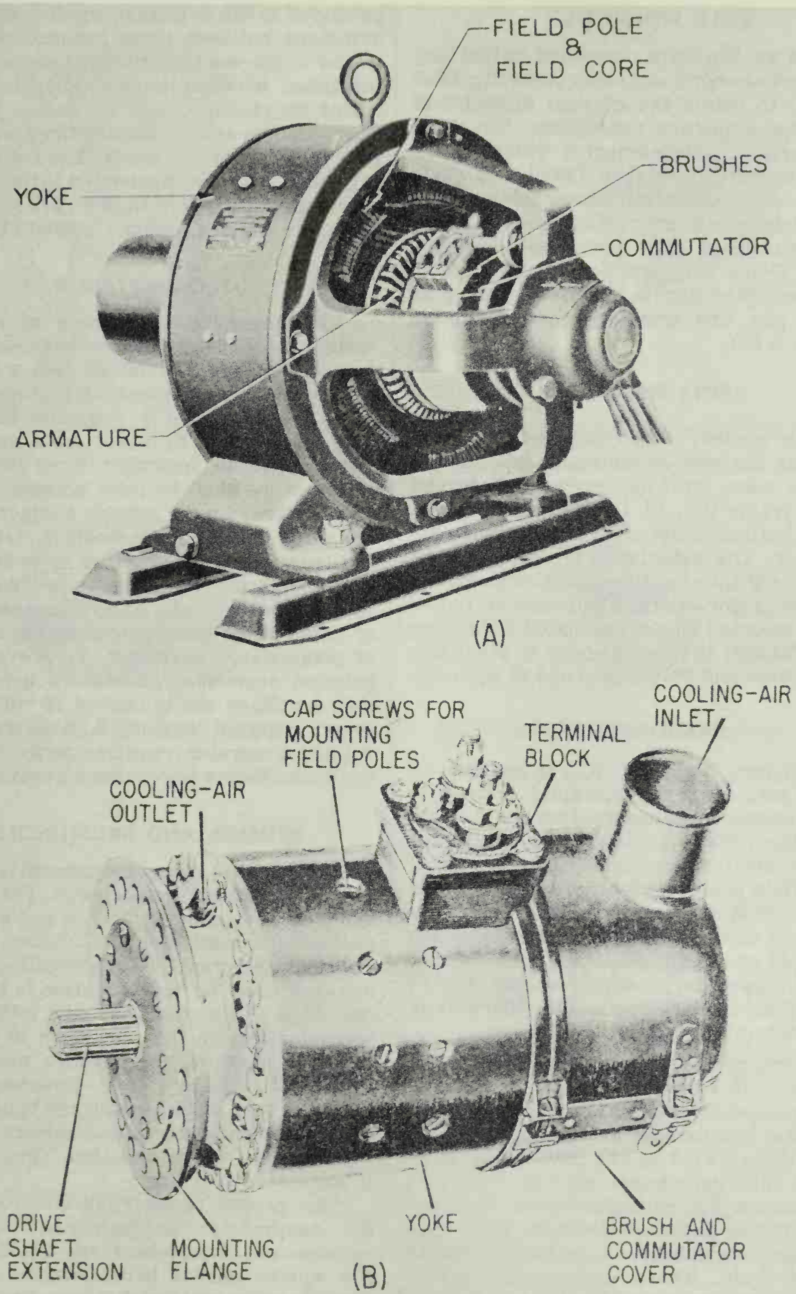

FIELD POLE & FIELD CORE
BRUSHES
YOKE
COMMUTATOR
ARMATURE
(A)
COOLING-AIR INLET
CAP SCREWS FOR MOUNTING FIELD POLES
TERMINAL BLOCK
COOLING-AIR OUTLET
DRIVE SHAFT EXTENSION
MOUNTING FLANGE
YOKE
BRUSH AND COMMUTATOR COVER
(B)

Figure 15-1.—D-c generators.

FIELD WINDINGS

The field windings are connected so that they produce alternate north and south poles (fig. 15-2 (A) and (F)) to obtain the correct direction of e.m.f. in the armature conductors. The field windings form an electromagnet which establishes the generator field flux. These field windings may receive current from an external d-c source or they may be connected directly across the armature, which then becomes the source of voltage. When they are so energized, they establish magnetic flux in the field yoke, pole pieces, air gap, and armature core, as shown in figure 15-2 (A).

POLE PIECES

The pole pieces, which support the field windings, are mounted on the inside circumference of the yoke, with capscrews that extend through the frame (fig. 15-1). These pole pieces are usually built of sheet steel laminations riveted together. The pole faces are shaped to fit the curvature of the armature, as shown in figure 15-2 (A). The preformed field coil shown in figure 15-2 (B) is mounted on the laminated core from the back. The coil is held securely in place between the frame and the flanged end of the pole.

ARMATURE

The armature (fig. 15-2 (C)) is mounted on a shaft and rotates through the field. If the output of the armature is connected across the field windings, the voltage and the field current at start will be small because of the small residual flux in the field poles. However, as the generator continues to run, the small voltage across the armature will circulate a small current through the field coils and the field will become stronger. This action causes the generator voltage to rise quickly to the proper value and the machine is said to "build up" its voltage.

The armature core is made of sheet steel laminations. In small machines these laminations are keyed directly to the shaft. In large machines the laminations are assembled on a spider which is keyed to the shaft. The outer surface of this cylindrical core is slotted to provide a means of securing the armature coils. Radial ventilating ducts are provided in the core by inserting spacers between the laminations at definite intervals. These ducts permit air to circulate through the core and to carry off heat produced in the armature winding and core. The armature coils on most generators are form-wound to the correct size and shape. Additional insulation between the core and windings is obtained by placing sheet insulation in the slots. The windings are secured by fiber wedges driven into the tops of the slots. The free ends of the armature coils are connected to the commutator riser, as indicated in figure 15-2 (C). The entire armature winding forms a closed circuit.

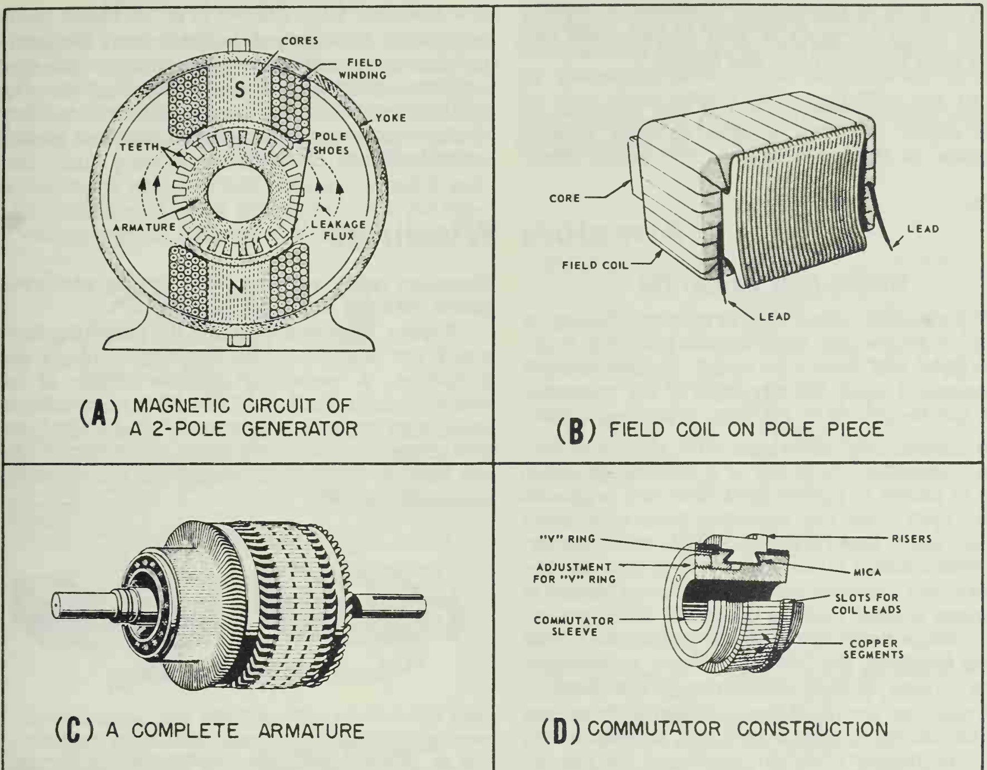
COMMUTATOR

The commutator consists of a number of wedge-shaped segments, or bars, of hard drawn copper that are assembled into a cylinder and held together by V-rings, as shown in figure 15-2 (D). The commutator segments are insulated from each other by sheet mica and the entire commutator is insulated from the supporting rings on the shaft by mica collars. Because the brushes bear on the outside surface of the commutator, better brush contact, less sparking, and less noise, are obtained by undercutting the mica to about 1/64 inch below the level of the commutator surface. The voltage and the number of poles in the generator determine the number of commutator segments. To prevent flashover between segments, generators are designed so that a voltage not to exceed 15 volts exists between adjacent segments. Therefore, a high-voltage generator requires more commutator segments than a low-voltage generator.

BRUSHES AND BRUSH HOLDERS

The brushes carry the current from the commutator to the external circuit. They are usually made of a mixture of carbon and graphite. For low-voltage machines the brushes are made of a mixture of graphite and a metallic powder. The brushes must be free to slide in their holders (fig. 15-2 (E)) so that they may follow any small irregularities in the curvature of the commutator. In addition, the brushes must be able to "feed in" as they wear. However, excessive play not only would encourage brush vibration, but also might cause misalinement of the brush with the axis of commutation. This would result in excessive sparking.

The proper pressure of the brushes against the commutator is maintained by means of springs and should be from 1-1/2 to 2 pounds per square inch of brush contact area. A low resistance connection between the brushes and


CORES
FIELD WINDING
YOKE
TEETH
POLE SHOES
S
N
ARMATURE
LEAKAGE FLUX
CORE
FIELD COIL
LEAD
LEAD
"V" RING
ADJUSTMENT FOR "V" RING
COMMUTATOR SLEEVE
RISERS
MICA
SLOTS FOR COIL LEADS
COPPER SEGMENTS
ADJUSTMENT FOR SPRING TENSION
PIGTAIL
SPRING FOR BRUSH PRESSURE
BRUSH
BRUSH HOLDER
+
−
RHEOSTAT
S
N
S
N

(A) MAGNETIC CIRCUIT OF A 2-POLE GENERATOR

(B) FIELD COIL ON POLE PIECE

(C) A COMPLETE ARMATURE

(D) COMMUTATOR CONSTRUCTION

(E) TYPICAL PIGTAIL BRUSH AND HOLDER

(F) SCHEMATIC WIRING DIAGRAM OF SHUNT GENERATOR

Figure 15-2.–D-c generator parts.

brush holders is maintained by means of braided copper wires, or pigtails, that are attached between each brush holder and brush.

The brush holders, which are attached to brush studs, hold the brushes in their proper positions on the commutator. The brush studs are fastened to a rocker arm, or brush holder yoke, that is attached to the frame. Multipolar generators usually have as many brush studs as there are main poles. The brush studs are of alternate positive and negative polarity and those of like polarity are connected together as indicated in figure 15-2 (F).

Armature Windings

SIMPLE COIL ARMATURE

The simplest generator armature winding is a loop or single coil. Rotating this loop in a magnetic field will induce an e.m.f. whose strength is dependent upon the strength of the magnetic field and the speed of rotation of the conductor.

A single-coil generator with each coil terminal connected to a bar of a 2-segment metal ring is shown in figure 15-3. The two segments of the split ring are insulated from each other and the shaft, thus forming a simple commutator. The commutator mechanically reverses the armature coil connections to the external circuit at the same instant that the direction of the generated voltage reverses in the armature coil. This action involves the process known as commutation, which is described later in the chapter.

When the coil rotates clockwise from the position shown in figure 15-3 (A), to the position shown in figure 15-3 (B), an e.m.f. is generated in the coil in the direction (indicated by the heavy arrows) that deflects the galvanometer to the right. Current flows out of the negative brush, through the galvanometer, and back to the positive brush to complete the circuit through the armature coil. If the coil is rotated to the position shown in figure 15-3 (C), the generated voltage and the current fall to zero, as in figure 15-3 (A). At this instant the brushes make contact with both bars of the commutator and short-circuit the coil. As the coil moves to the position shown in figure 15-3 (D), an e.m.f. is generated again in the coil but of opposite polarity.

The e.m.f.'s generated in the two sides of the coil shown in figure 15-3 (D), are in the reverse direction to that of the e.m.f.'s shown in figure 15-3 (B). Since the bars of the commutator have rotated with the coil and are connected to opposite brushes, the direction of the flow of current through the galvanometer remains the same. The e.m.f. developed across the brushes is pulsating and unidirectional (in one direction only), varying twice during each revolution between zero and maximum.

Figure 15-4 is a graph of the pulsating direct e.m.f. for one revolution of a single-loop 2-pole armature. A pulsating direct voltage of this characteristic (called RIPPLE) is unsuitable for most applications. Therefore, in practical generators more coils and more commutator bars are used to produce an output voltage waveform with less ripple.

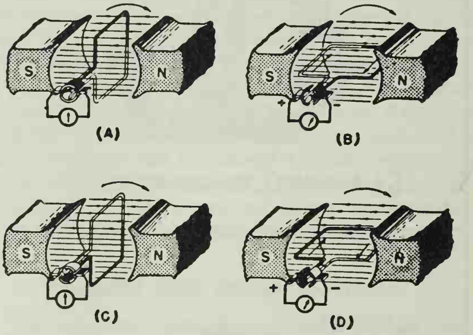


Figure 15-3.—Single-coil generator with commutator.

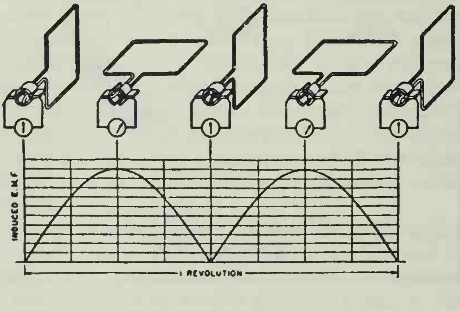


Figure 15-4.—Voltage from a single-coil armature.

EFFECT OF MORE COILS

Figure 15-5 shows the reduction in ripple component of the voltage obtained by the use of two coils instead of one. Since there are now four commutator segments in the commutator and only two brushes, the voltage cannot fall any lower than point A; Therefore, the ripple is limited to the rise and fall between points A and B. By adding still more armature coils, the ripple voltage can be reduced still more.

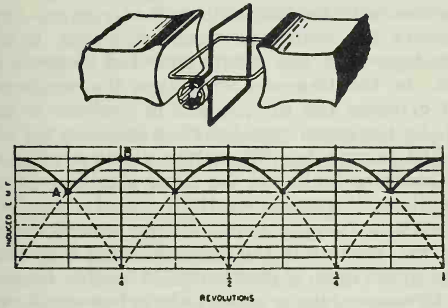
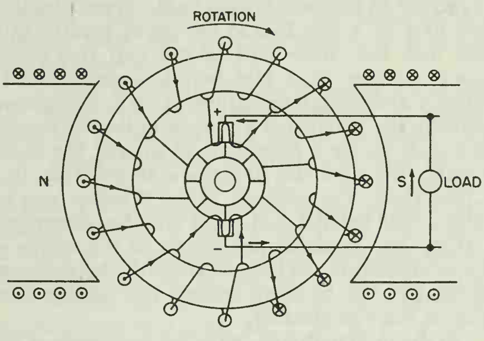


Figure 15-5.—Voltage from a two-coil armature.

GRAMME-RING WINDING

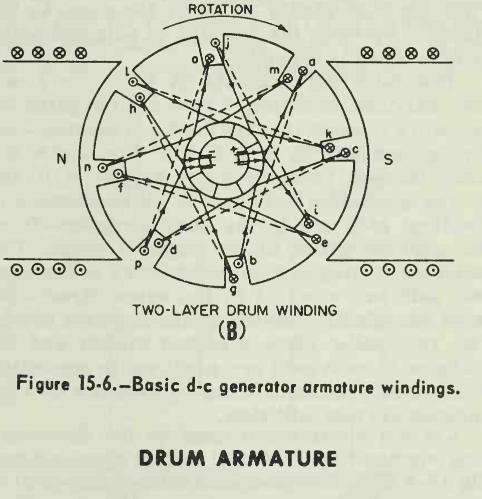
A Gramme-ring winding (fig. 15-6) is formed by winding insulated wire around a hollow iron ring and tapping it at regular intervals to the commutator bars. The portions of the windings on the inside of the ring cut practically no flux and act as connectors for the active portions of the conductors, which lie on the outer surface of the ring. Because only a small fraction of the conductor is used to generate voltage in such a winding, a relatively large amount of copper is required to produce a given voltage. The schematic wiring diagram of a Gramme-ring winding is frequently used as a simplified equivalent circuit for the practical but more complex drum armature wiring diagrams. The Gramme-ring winding is used in this discussion only to simplify the drum winding circuits.

In the 2-pole winding of figure 15-6 (A), there are two parallel paths for armature current between the brushes. One path is through the coils on the left side and the other is through the coils on the right side. The voltage between the brushes is the vector sum of the voltages generated in all the coils of each path. No circulating current flows between the two paths because the generated voltages in the two paths are equal and in opposition. The polarity of the brushes may be determined by the left-hand rule for generator action. The negative terminal is the one from which electrons flow out to the load; the positive terminal is the one to which the electrons return from the load.



GRAMME-RING WINDING

(A)



TWO-LAYER DRUM WINDING

(B)

Figure 15-6.—Basic d-c generator armature windings.

DRUM ARMATURE

In the basic drum winding shown in figure 15-6 (B), all the conductors lie in slots near the surface of the armature. The armature conductors are indicated in the figure as circles. Those on the left contain a dot to indicate that the direction of generated voltage is toward the observer; those on the right contain an x to show that the direction of the generated voltage is away from the observer. The dotted lines connecting the circles represent end connections on the back of the armature between the two halves of each coil. The solid lines between the commutator and the armature conductors represent the end connections on the front of the armature between the coils and commutator segments.

There are 8 coils, 8 slots, and 8 commutator segments in this simplified basic drum winding. One half of a coil lies in the upper portion of a slot and the other half of the coil lies in the lower portion of a slot that is approximately halfway around the armature. This arrangement permits the generated voltages in the two halves of a coil to be a maximum at almost the same instant, because the armature is rotating in a 2-pole field. The polarity of the brushes may be determined by the left-hand rule for generator action. The brushes are shown on the inside of the commutator surface to simplify the drawing. Normally, the brushes contact the outside surface of the commutator.

In drum armatures, with the exception of the coil-end connections, all of the copper is used to generate the e.m.f. The distance between the two sides of a coil is known as the COIL PITCH. This distance should be about the same as the distance between the centers of adjacent poles as mentioned previously.

The following analysis is made for a no-external-load condition. There are two paths for armature current through the drum winding—one through conductors *a, b, c, d, e, f, g,* and *h;* the other through conductors *i, j, k, l, m, n, o,* and *p.* The generated voltages in all conductors in the first path are in the same direction—from the positive brush to the negative brush. The generated voltages in all conductors in the second path are also all in the same direction—from the positive brush to the negative brush. The two paths form a closed circuit and the voltages of each path are equal and in opposition with respect to each other. Therefore no circulating current will flow.

Certain similarities exist in the Gramme-ring winding (fig. 15-6 (A)) and the drum winding (fig 15-6 (B)). The generated voltage distribution is the same. The number of paths for load current is the same. In both types, when a brush contacts two segments, a coil is short-circuited. In both types, the brushes are positioned so that only coils that are moving approximately parallel to the field are short-circuited. That is, a coil is short-circuited only at the exact instant that it has no voltage induced in it. Thus, sparking is minimized. In both types, there are 8 commutator bars and 2 brushes and the armatures are wound for 2-pole fields. Also, in both types there are single-turn coils and 16 active conductors in which the voltage of the machine is generated.

The differences that exist in the two types of armatures are in the position of the brush axis, the method of mounting the coils, and the path for the magnetic field flux. In the Gramme-ring winding the brush axis is perpendicular to the field axis. In the drum winding the brush axis coincides with the field axis. In the Gramme-ring armature the coils are wound on a ring. In the drum type they are preformed and inserted in slots. In the Gramme-ring type the magnetic field crosses the air gap and is confined to the ring. In the drum type the field crosses the air gap and permeates the entire cross section of the armature including the outer slotted portion as well as the inner section. Finally, the end connections form a much higher percentage of the total winding in the Gramme-ring type than in the drum type. It is principally for this reason that Gramme-ring armatures have been replaced by the more efficient drum-type armature.

SIMPLEX LAP WINDING

As mentioned previously, direct-current armatures are generally wound with preformed coils, as shown in figure 15-7. The term "span" is the distance from one winding element of a coil to the other winding element of the same coil and is usually given in terms of the number of slots included between them. A winding element is a coil side consisting of one or more active (face) conductors in series and taped together to form that part of the coil that is inserted in the armature slot. The span of the armature coil should be about equal to the peripheral distance between the centers of adjacent field poles, so that the voltages generated in the two sides of the coil will be in series addition. This distance is called POLE PITCH. When the span of a coil is less than the pole pitch the winding is called a FRACTIONAL-PITCH WINDING. A fractional pitch coil can be as low as 0.8 pole pitch. Fractional pitch coils have reduced e.m.f. because the coil side voltages do not reach their maximum values at the same time. Ordinarily, the reduction in e.m.f. is small. The savings in copper, in shorter end-connections, warrants the loss.

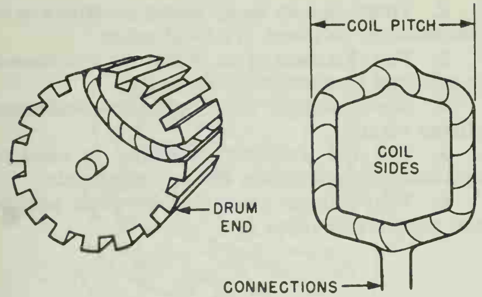
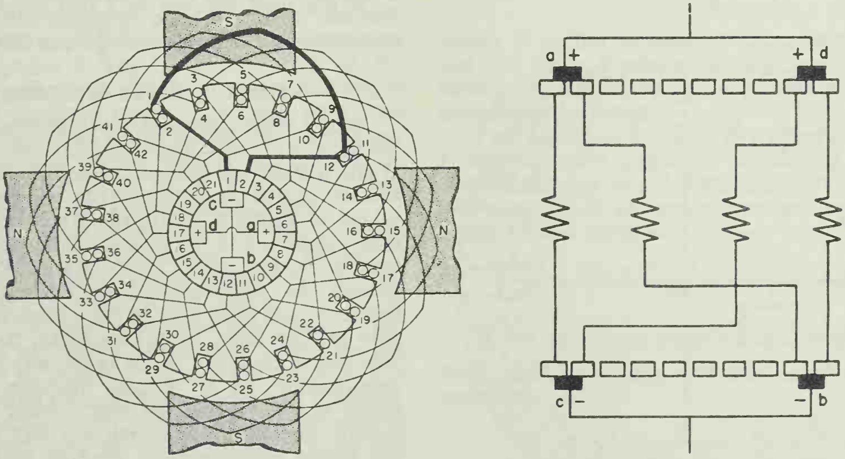


Figure 15-7.—Formed armature coil for 4-pole armature.

Direct-current armature windings are generally 2-layer windings. In this arrangement, the coils are placed on the armature with one side of a coil occupying the top of one slot and its other side occupying the bottom of another slot. The distance between the slots is approximately 1 pole span. Such an arrangement allows the windings to fit readily on the armature with an equal number of coils and slots. Thus each slot contains two layers of conductors in which voltages are generated as the armature rotates through the field. This arrangement is shown in the 2-layer drum winding of figure 15-6 (B).

A 4-pole simplex-lap winding is shown in figure 15-8. Starting with commutator bar 1, the circuit may be traced through the heavy black coil to the adjacent commutator bar 2. The trace may be continued through successive coils until the entire armature circuit has been traced from one end to the other. Upon reentering the starting commutator bar 1, the trace is completed. Thus, the circuit is seen to be a closed-circuit winding

There are four groups of coils generating the same voltage between brushes of opposite polarity in the example shown in figure 15-8. One group consists of coils occupying winding spaces 1, 12, 3, 14, 5, 16, 7, 18, 9, and 20. A second group consists of coils occupying winding spaces 11, 22, 13, 24, 15, 26, 17, 28, 19, and 30. A third group consists of coils occupying winding spaces 21, 32, 23, 34, 25, 36, 27, 38, 29, and 40. The fourth group consists of coils occupying winding spaces 31, 42, 33, 2, 35, 4, 37, 6, 39, 8, 41, and 10. These four groups of coils are placed in parallel by connecting the two positive brushes together and the two negative brushes together as indicated in the schematic diagram of figure 15-8 (B). No circulating current flows between these four parallel paths when no load is connected between the positive and negative brushes,



ARMATURE WINDING
(A)

SIMPLIFIED CIRCUIT
(B)

Figure 15-8.—Simplex-lap 4-pole armature winding.

because the voltage of each of the groups is equal and of opposite polarity to the voltages of the other groups.

A simplified schematic of the 4-pole simplex-lap armature winding is shown in figure 15-9. Connecting a load between the positive and negative brushes causes current to flow through the armature in these four paths. The current is distributed equally in the four paths. Thus if the total output current of the armature is 400 amperes, each path through the armature will carry 100 amperes. In this winding there are as many parallel paths for current through the armature as there are poles in the field.

The simplex-lap winding described in this chapter is the simplest type of lap winding. It is identified as a single winding to distinguish it from more complex double and triple lap windings. It is single-reentrant—that is, the winding closes on itself at the end of one complete turn around the armature. This arrangement distinguishes the winding from more complex types that reenter upon themselves after one, two, or three complete turns around the armature. The more complex lap windings are described in the texts that pertain to particular ratings.

The characteristics of the (single) simplex-lap winding may be summarized as follows:

1. There are as many paths for current as there are field poles.

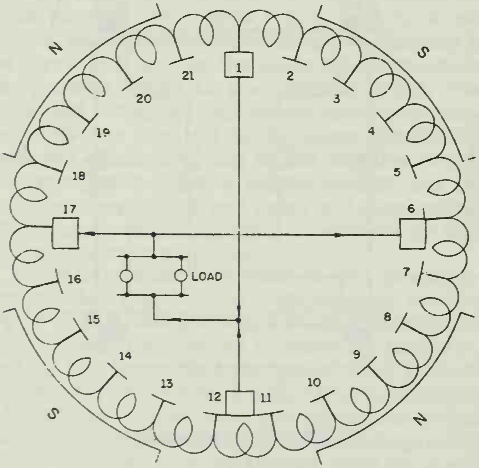


Figure 15-9.—Simplified schematic of simplex-lap 4-pole armature winding.

2. There are as many brush positions on the commutator as there are field poles.

3. The two ends of an armature coil connect to adjacent commutator segments.

4. The armature winding forms a continuous closed circuit.

5. The lap armature winding is used for relatively high-current low-voltage loads.

6. The voltage generated between positive and negative brushes is

$$E = \frac{\Phi ZN}{10^8},$$

where E is the generated e.m.f. in volts, Z the number of armature face conductors, Φ the lines of magnetic flux per pole, and N the armature speed in revolutions per second.

A face conductor lies in a slot and generates a voltage as the armature rotates. An armature coil includes one or more turns, each of which consists of two face conductors and their respective end connections. For example, a 4-pole d-c generator with a simplex-lap armature winding having 10^6 lines of magnetic flux per pole, 440 armature conductors, and a speed of 50 revolutions per second (3,000 r.p.m.) has a generated voltage of

$$E = \frac{10^6 \times 440 \times 50}{10^8} = 220 \text{ volts.}$$

If the load current is 1,000 amperes, each armature coil will carry $\frac{1,000}{4}$, or 250 amperes.

SIMPLEX WAVE WINDING

In the single simplex-wave winding (fig. 15-10) groups of coils under similar pairs of poles at any instant are generating equal voltages and are connected in series. This winding is also called a SERIES WINDING. Each coil has its ends connected to the commutator bars that are two pole spans apart. This distance is measured around the armature circumference from the center of one field pole to the center of the next pole of like sign. In this example, the distance covered by two pole spans is halfway around the commutator; in a 6-pole machine, two pole spans are one-third the way around; and in an 8-pole machine, one-fourth the way around. In the single simplex-wave winding there are as many coils connected in series between adjacent commutator bars as there are pairs of poles in the field. In this example there are two pairs of poles, so there are two coils in series between adjacent commutator bars. This arrangement

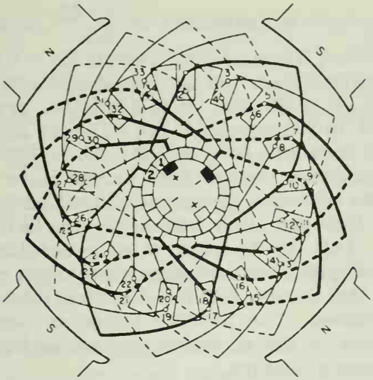


Figure 15-10.—Single simplex-wave winding.

may be seen by starting at segment 1 and tracing through the circuit of the two coils occupying winding spaces 1, 10, 17, and 26, and ending at commutator segment 2.

The single simplex-wave winding is a closed-circuit winding as may be seen by starting with one coil and tracing through the entire armature circuit to complete the trace by ending at the starting position. In the single simplex wave-wound armature there are two paths for current regardless of the number of poles for which it is wound and regardless of the number of brushes. Starting with the upper positive brush, one path includes the armature conductors that occupy winding spaces 1, 10, 17, 26, 33, 8, 15, 24, 31, 6, 13, 22, 29, 4, 11, 20, 27, and 2, returning to the upper negative brush. The other path from the upper positive brush includes the armature conductors that occupy winding spaces 28, 19, 12, 3, 30, 21, 14, 5, 32, 23, 16, 7, 34, 25, 18, and 9, returning to the upper negative brush.

Although four brushes are shown, only two are required. The full voltage of the winding is developed across the upper brushes, and the full voltage is also developed across the lower brushes. The load current divides equally between the two pairs of brushes when they are connected in parallel because the resistance of the two paths through the armature is the same. For example, if the armature has a 20-ampere load at 220 volts the upper brushes alone will carry 20 amperes at 220 volts. Adding the lower brushes will reduce the current to 10 amperes per brush. If the commutator is designed for four brushes, the removal of one pair will overload the remaining brushes unless the load is halved. However, where commutators are inaccessible, wave windings permit the use of two brush positions irrespective of the number of poles, so that servicing the brushes and commutator is facilitated.

The characteristics of the simplex-wave winding may be summarized as follows:

1. There are two parallel paths irrespective of the number of field poles.
2. There is a minimum of two brush positions irrespective of the number of field poles.
3. The two ends of a coil connect to commutator segments that are two pole spans apart (fig. 15-10).
4. The winding has relatively high voltage and low current.
5. The winding forms a continuous closed circuit.
6. There are as many coils in series between adjacent commutator segments as there are pairs of poles in the field.
7. The voltage generated between positive and negative brushes is

$$E = \frac{\Phi ZNP}{10^8},$$

where P is the number of pairs of field poles and the other symbols are the same as those used in the equation for generated voltage in a simplex-lap winding.

For example, a 6-pole d-c generator having a simplex-wave armature winding, 1.05×10^6 lines of flux per pole, 3,500 armature conductors, and a speed of 10 revolutions per second (600 r.p.m.) has a generated voltage of

$$E = \frac{\Phi ZNP}{10^8} = \frac{1.05 \times 10^6 \times 3{,}500 \times 10 \times 3}{10^8} = 1{,}100 \text{ volts.}$$

If the armature supplies 200 amperes to a load, each armature coil will carry $\frac{200}{2} = 100$ amperes.

Armature Losses

There are three losses in every d-c generator armature. These are (1) the I^2R or copper loss in the winding, (2) the eddy current loss in the core, and (3) the hysteresis loss due to the friction of the revolving magnetic particles in the core.

COPPER LOSSES

The copper loss is the power lost in heat in the windings due to the flow of current through the copper coils. This loss varies directly with the armature resistance and as the square of the armature current. The armature resistance varies with the length of the armature conductors and inversely with their cross-sectional area.

Armature conductor size is based on an allowance of from 300 to 1,200 circular mils per ampere. For example, a 2-pole armature that is required to supply 100 amperes may use a wire size based on 800 circular mils per ampere, or $\frac{100}{2} \times 800 = 40{,}000$ circular mils. This value corresponds to a No. 4 wire. Very small armature windings may use only 300 circular mils per ampere with a resulting high current density. Large generators (5,000 kw.) require an allowance of 1,200 circular mils per ampere with a resulting low current density in the windings. These variations are the result of the variable nature of the heat-radiating ability of the armature conductors.

Very small round conductors have a much higher ratio of surface to volume than do large round conductors. For example, a 0.1-inch diameter round conductor of a given length has a surface-to-volume ratio of

$$\frac{4\pi D}{\pi D^2}\text{, or } \frac{4}{0.1} = 40.$$

A 1.0-inch diameter conductor of the same length has a surface-to-volume ratio of $\frac{4}{1}$, or 4. Since the heat-radiating ability of a round conductor varies as the ratio of its surface to volume, the 0.1-inch diameter conductor has $\frac{40}{4}$, or 10 times the heat radiating ability of the 1-inch diameter conductor, other factors being equal.

High-speed generators use a lower circular-mil-per-ampere allowance than low-speed generators because of better cooling. The temperature rise is limited by ventilating ducts, and in some cases by the use of forced ventilation, as in aircraft d-c generators.

The hot resistance of an armature winding is higher that its cold resistance. A 2.5° centigrade increase in temperature of a copper conductor corresponds to an increase in resistance of approximately 1 percent. For example, if the no-load temperature of an armature winding is 20° C. and its full-load temperature is 70° C., the increase in resistance is $\frac{70 - 20}{2.5}$, or 20 percent. Thus, if the no-load resistance is 0.05 ohm between brushes, the hot resistance will be 1.2 x 0.05, or 0.06 ohm. If the full-load armature current is 100 amperes, the full-load armature copper loss will be $(100)^2 \times 0.06$, or 600 watts. The armature copper loss varies more widely with the variation of electrical load on the generator than any other loss occurring in the machine. This is because most generators are constant-potential machines supplying a current output that varies with the electrical load across the brushes. The limiting factor in load on a generator is the allowable current rating of the generator armature.

The armature circuit resistance includes the resistance of the windings between brushes of opposite polarity, the brush contact resistance, and the brush resistance.

EDDY-CURRENT LOSSES

If a d-c generator armature core were made of solid iron (fig. 15-11 (A)) and rotated rapidly in the field, excessive heating would develop even with no-load current in the armature windings. This action would be the result of a generated voltage in the core itself. As the core rotates, it cuts the lines of magnetic field flux at the same time the copper conductors of the armature cut them. Thus, induced currents alternate through the core, first in one direction and then in the other, with accompanying generation of heat.

These induced currents are called EDDY CURRENTS. They are kept to a low value by sectionalizing (laminating) the armature core. For example, if the core is split into two equal parts (fig. 15-11 (B)) and these parts are insulated from each other, the voltage induced in each section of iron is halved and the resistance of the eddy-current paths is doubled (resistance varies inversely with the cross-sectional area). If 10 volts is induced in the core (fig. 15-11 (A)) and the resistance of the path for eddy currents is 1 ohm, the eddy-current loss is $\frac{E^2}{R}$, or $\frac{10^2}{1}$ = 100 watts. The voltage is each section (fig. 15-11 (B)) will be $\frac{10}{2}$, or 5 volts, because the length is halved and the resistance of the eddy-current path for each section is 2 ohms. The loss in each section is $\frac{E^2}{R}$, or $\frac{5^2}{2}$ = 12.5 watts, and the total

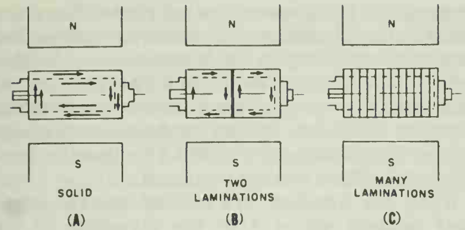


Figure 15-11.—Eddy currents in d-c generator armature cores.

loss in both sections is 12.5 x 2, or 25 watts. This value represents one-fourth of the power loss in figure 15-11 (A).

Reducing the thickness of the core to one-half its original value reduces the loss to one-fourth of the original loss. Thus, eddy-current losses vary as the square of the thickness of the core laminations.

If the armature core is sufficiently subdivided into multiple sections or laminations (fig. 15-11 (C)), the eddy-current loss can be reduced to a negligible value. Reducing the thickness of the laminations reduces the magnitude of the induced e.m.f. in each section and increases the resistance of the eddy-current paths. Laminations in small generator armatures are 1/64 inch thick. The laminations are insulated from each other by a thin coat of lacquer or in some instances simply by the oxidation of the surfaces due to contact with the air while the laminations are being annealed. The insulation need not be high because the voltages induced are very small.

All electrical rotating machines are laminated to reduce eddy-current losses. Transformer cores are laminated for the same reason.

The eddy-current loss is also influenced by speed and flux density. Because the induced voltage, which causes the eddy-currents to flow, varies with the speed and flux density, the power loss, $\frac{E^2}{R}$, varies as the square of the speed and the square of the flux density.

HYSTERESIS LOSS

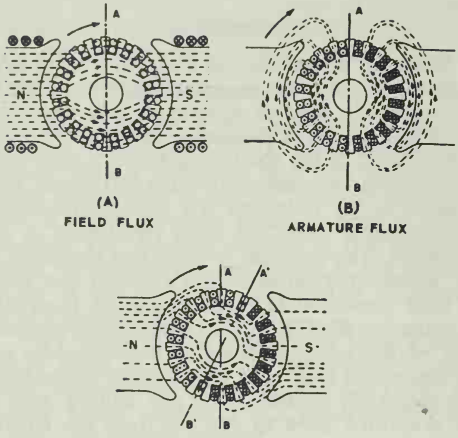
When an armature revolves in a stationary magnetic field, the magnetic particles of the armature are held in alinement with the field in varying numbers depending upon the strength of the field. If the field is that of a 2-pole generator, these magnetic particles will rotate, with respect to the particles not held in alinement, one complete turn for each revolution of the armature. The rotation of magnetic particles in the mass of iron produces friction and heat.

Heat produced in this manner is identified as magnetic HYSTERESIS LOSS. The hysteresis loss varies with the speed of the armature and the volume of iron. The flux density varies from approximately 50,000 lines per square inch in the armature core to 130,000 lines per square inch in the iron between the bottom of adjacent armature slots (called the TOOTH ROOT). Heat-treated silicon steel having a low hysteresis loss is used in most d-c generator armatures. After the steel has been formed to the proper shape, the laminations are heated to a dull red heat and allowed to cool. This annealing process reduces the hysteresis loss to a low value.

Armature Reaction

Armature reaction in a generator is the effect on the main field of the armature acting as an electromagnet. With no armature current, the field is undistorted, as shown in figure 15-12 (A). This flux is produced entirely by the ampere-turns of the main field windings. The neutral plane AB is perpendicular to the direction of the main field flux. When an armature conductor moves through this plane its path is parallel to the undistorted lines of force and the conductor does not cut through any flux. Hence no voltage is induced in the conductor. The brushes are placed on the commutator so that they short-circuit coils passing through the neutral plane. With no voltage generated in the coils, no current will flow through the local path formed momentarily between the coils and segments spanned by the brush. Therefore, no sparking at the brushes will result.

When a load is connected across the brushes, armature current flows through the armature conductors, and the armature itself becomes a source of magnetomotive force. The effect of the armature acting as an electromagnet is considered in figure 15-12 (B), with the assumption that the main field coils are deenergized and full-load current is introduced to the armature circuit from an external source. The currents in the conductors on the left of the neutral plane all carry current toward the observer, and those on the right carry current away from the observer. These directions are the same as those in which the current would flow if it were under the influence of the normal e.m.f. generated in the armature with normal field excitation.



(A)
FIELD FLUX

(B)
ARMATURE FLUX

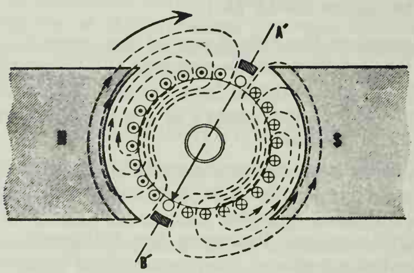
(C)
RESULTANT FLUX

Figure 15-12.—Flux distribution in a d-c generator.

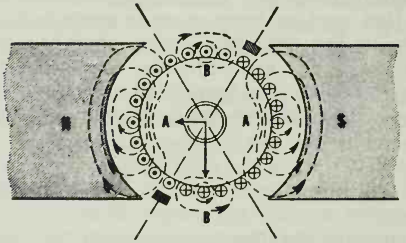
These armature current-carrying conductors establish a magnetomotive force that is perpendicular to the axis of the main field, and in the figure the force acts downward. This magnetizing action of the armature current is called CROSS MAGNETIZATION and is present only when current flows through the armature circuit. The amount of cross magnetization produced is proportional to the armature current.

When current flows in both the field and armature circuits, the two resulting magnetomotive forces distort each other. They twist in the direction of rotation of the armature. The mechanical (no load) neutral plane, AB (fig. 15-12 (C)), is now advanced to the electrical (load) neutral plane, A'B'. When armature conductors move through plane A'B' their paths are parallel to the distorted field and the conductors cut no flux, hence no voltage is induced in them. The brushes must therefore be moved on the commutator to the new neutral plane. They are moved in the direction of armature rotation. The absence of sparking at the commutator indicates correct placement. The amount that the neutral plane shifts is proportional to the load on the generator because the amount of cross-magnetizing magnetomotive force is directly proportional to the armature current.

When the brushes are shifted into the electrical neutral plane A'B' the direction of the armature magnetomotive force is downward and to the left, as shown in figure 15-13 (A), instead of vertically downward. The armature magnetomotive force may now be resolved into two components, as shown in figure 15-13 (B).



(A)
ARMATURE FLUX



(B)
DEMAGNETIZING AND CROSS-MAGNETIZING COMPONENTS

Figure 15-13.—Effect of brush shift on armature reaction.

The conductors included at the top and bottom of the armature within sectors BB produce a magnetomotive force that is directly in opposition to the main field and weakens it. This component is called the ARMATURE DEMAGNETIZING M.M.F. The conductors included on the right and left sides of the armature within sector AA produce a cross-magnetizing m.m.f. at right angles to the main field axis. This cross-magnetizing force tends to distort the field in the direction of rotation. As mentioned previously, the distortion of the main field of the generator is the result of ARMATURE REACTION. Armature reaction occurs in the same manner in multipolar machines.

COMPENSATING FOR ARMATURE REACTION

The effects of armature reaction are reduced in d-c machines by the use of (1) high flux density in the pole tips, (2) a compensating winding, and (3) commutation poles.

The cross-sectional area of the pole tips is reduced by building the field poles with laminations having only one tip. These laminations are alternately reversed when the pole core is stacked so that a space is left between alternate laminations at the pole tips. The reduced cross section of iron at the pole tips increases the flux density so that they become saturated and the cross-magnetizing and demagnetizing forces of the armature will not affect the flux distribution in the pole face to as great an extent as they would at reduced flux densities.

The compensating winding consists of conductors imbedded in the pole faces parallel to the armature conductors. The winding is connected in series with the armature and is arranged so that the ampere-turns are equal in magnitude and opposite in direction to those of the armature. The magnetomotive force of the compensating winding therefore neutralizes the armature magnetomotive force, and armature reaction is practically eliminated. Because of the relatively high cost, compensating windings are ordinarily used only on high-speed and high-voltage generators of large capacity.

Commutating poles are discussed after the description of the process of commutation.

Commutation

Commutation is the process of reversing the current in the individual armature coils and conducting the direct current to the external circuit during the brief interval of time required for each commutator segment to pass under a brush. In figure 15-14, commutation occurs simultaneously in the two coils that are undergoing momentary short circuit by the brushes—coil *B* by the negative brush, and the diametrically opposite coil by the positive brush. As mentioned previously, the brushes are placed on the commutator in a position that short-circuits the coils that are moving through the electrical neutral plane because there is no voltage generated in the coils at the time and no sparking occurs between commutator and brush.

There are two paths for current through the armature winding. If the load current is 100 amperes, each path will contain a current of 50 amperes. Thus each coil on the left side carries 50 amperes in a given direction and each coil on the right side carries a current of 50 amperes in the opposite direction. The reversal of the current in a given coil occurs during the time that particular coil is being short-circuited by a brush. For example, as coil *A* approaches the negative brush it is carrying the full value of 50 amperes which flows through commutator segment 1 and the left half of the negative brush where it joins 50 amperes from coil *C*.

At the instant shown, the negative brush spans half of segment 1 and half of segment 2. Coil *B* is on short circuit and is moving parallel to the field so that its generated voltage is zero, and no current flows through it. As rotation continues in a clockwise direction the negative brush spans more of segment 1 and less of segment 2. Consider, for example, the interval included between the instant shown in the figure and the instant that the negative brush spans only segment 1. During this time the current in segment 1 increases from 50 to 100 amperes and the current in segment 2 decreases from 50 to 0 amperes. When segment 2 leaves the brush, no current flows from segment 2 to the brush and commutation is complete.

As coil *A* continues into the position of coil *B* the current in *A* decreases to zero. Thus, the current in the coils approaching the brush is reducing to zero during the brief interval of time that it takes for coil *A* to move to the position of coil *B*. During this time the flux collapses around the coil and induces an e.m.f. of self-induction which opposes the decrease of current. Thus, if the e.m.f. of self-induction is not neutralized, the current will not decrease in coil *A*

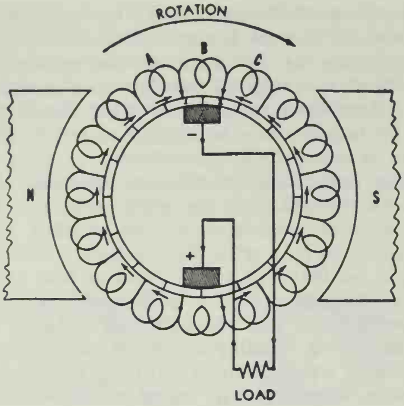


Figure 15-14.—Commutation in a d-c generator.

and the current in the coil lead to segment 1 will not be zero when segment 1 leaves the brush. This delay causes a spark to form between the toe of the brush and the trailing edge of the segment. As the segment breaks contact with the brush, this action burns and pits the commutator.

The reversal of current in the coils takes place very rapidly. For example, in an ordinary 4-pole generator, each coil passes through the process of commutation several thousand times per minute. It is important that commutation be accomplished without sparking to avoid excessive commutator wear.

ADVANCING THE BRUSHES

The e.m.f. of self-induction in the armature coils is caused by the inductance of the coils and the changing current in them and cannot be eliminated. The effects of this e.m.f. can be neutralized however, by introducing into the coil during the process of commutation an e.m.f. that is equal and in opposition to the induced e.m.f. This neutralization can be accomplished by shifting the brushes in the direction of rotation or by using interpoles (commutating poles).

If the brushes are shifted in the direction of rotation until the coils undergoing commutation cut a small amount of flux from the on-coming main pole, sufficient e.m.f. is induced to neutralize the effect of the self-induced e.m.f. This action allows the coil current to decrease to zero and increase to the desired values in the opposite direction without sparking at the brushes.

The flux necessary to generate the e.m.f. that neutralizes the e.m.f. of self-induction is called the COMMUTATING FLUX. This method of reducing sparking at the brushes is satisfactory only under steady-load conditions because the amount of commutating flux required varies with the load and, therefore, the brushes must be shifted with each change in load.

COMMUTATING POLES

Commutating poles, or interpoles, provide the required amount of commutating flux without shifting the brushes from mechanical neutral. They are narrow auxiliary poles located midway between the main poles, as shown in figure 15-2 (F). They establish a flux in the proper direction and of sufficient magnitude to produce satisfactory commutation. They do not contribute to the generated e.m.f. of the armature as a whole because the voltages generated by their fields cancel each other between brushes of opposite polarity.

The interpole magnetomotive force neutralizes that portion of the armature reaction within the zones of commutation and produces the proper flux to generate an e.m.f. in the short-circuited coil that is equal and opposite to the e.m.f. of self-induction. Thus, no sparking occurs at the brushes and ‘‘black’’ commutation indicates the ideal condition. Because both the armature reaction and the self-induced e.m.f. in the commutated coils vary with armature current, the interpole flux varies with the armature current. This condition is obtained by connecting the interpole windings in series with the armature and operating the interpole iron at flux densities well below saturation. The magnetic polarities are such that an interpole always has the same polarity as the adjacent main field pole in the DIRECTION OF ROTATION. This relation always exists for d-c generators.

Motor Reaction in a Generator

Whenever a generator delivers current to a load, the load current creates an opposition force that opposes the rotation of the generator armature. An armature conductor is represented in figure 15-15. When the conductor is stationary, no voltage is generated and no current flows; hence, no force acts on the conductor. When the conductor is moved downward and the circuit is completed through an external load, current flows through the conductor in the direction indicated, setting up lines of force around it that have a clockwise direction.

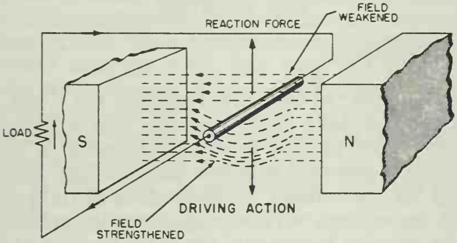


Figure 15-15.—Motor reaction in a generator.

The interaction of the conductor field and the main field of the generator weakens the field above the conductor and strengthens it below the conductor. The field consists of lines that act like stretched rubber bands. Thus, an upward reaction force is produced that acts in opposition to the downward driving force applied to the generator armature. If the current in the conductor increases, the reaction force increases, and more force must be applied to the conductor to keep it from slowing down.

With no armature current, no magnetic reaction exists and the generator input power is low. As the armature current increases, the reaction of each armature conductor against rotation increases and the driving power to maintain the generator armature speed must be increased. If the prime mover driving the generator is a gasoline engine, this effect is accomplished by opening the throttle on the carburetor. If the prime mover is a steam turbine, the main steam-admission valve is opened wider, thus permitting more steam to flow through the turbine.

D-C Generator Characteristics

METHODS OF CONNECTING THE FIELD WINDINGS

Usually d-c generators are classified according to the manner in which the field windings are connected to the armature circuit (fig. 15-16).

A SEPARATELY EXCITED D-C GENERATOR is indicated in the simplified schematic diagram of figure 15-16 (A). In this machine the field windings are energized from a separate d-c source other than its own armature.

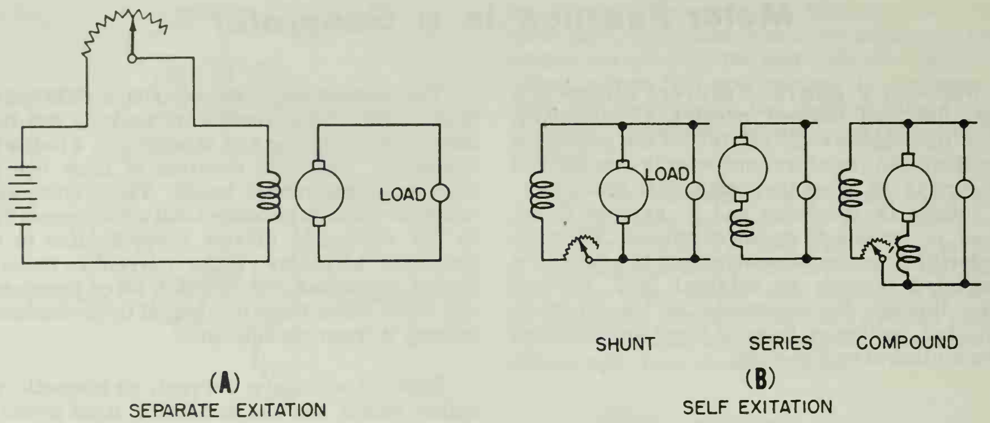
A SHUNT GENERATOR has its field windings connected across the armature in shunt with the load, as shown in figure 15-16 (B). The shunt generator is widely used in industry.

A SERIES GENERATOR has its field windings connected in series with the armature and load, as shown in figure 15-16 (B). Series generators are seldom used.

COMPOUND GENERATORS contain both series and shunt field windings, as shown in figure 15-16 (B). Compound generators are widely used in industry.

FIELD SATURATION CURVES

The strength of the field of a d-c generator depends on the number of ampere-turns in the field windings and the reluctance of the magnetic circuit. The number of turns is generally fixed. Hence, the ampere-turns vary directly with the field current. The generated voltage is directly proportional to the product of the field strength and the speed. Thus, if the field strength is zero or the speed is zero, the generated voltage will be zero. As the current through the field windings increases, the field flux and voltage output will increase. The field strength, however, is not directly proportional to the field current because the reluctance of the magnetic circuit



(A)
SEPARATE EXITATION

(B)
SELF EXITATION

Figure 15-16.—Types of d-c generators.

varies with the degree of magnetization. With increasing flux density in the field and armature iron the permeability decreases, thereby increasing the reluctance of the magnetic circuit and it becomes more difficult to increase the voltage.

Certain operating characteristics of the d-c generator are very closely related to the no-load and the full-load field saturation curves of the machine. The no-load saturation curve is determined with no armature current and the full-load saturation is determined with full-load armature current. The speed is held constant for both curves and the field current is increased in equal steps. The terminal voltage corresponding to each value of field current is plotted and forms the field saturation curves as shown in figure 15-17. The no-load saturation curve is preferably taken with the field separately excited. However, for a shunt or a compound generator these curves can be taken with the machine self-excited because the armature voltage drop due to the shunt field current is negligible.

With a certain field current, *OA* (fig. 15-17), a no-load e.m.f. of *AD* volts is generated, but the terminal voltage at full load is *AF*. The difference, *DF*, is caused by the armature *IR* drop and armature reaction. The saturation curves bend to the right at high values of field current and thereby show the tendency of the field iron to saturate. The no-load saturation curve is the magnetization curve of the machine. Because this curve is obtained with no armature current, the observed voltage is the generated e.m.f. of the machine. At zero field current the e.m.f. is not zero because of the residual flux of the machine. This fact is important because a self-excited generator depends on residual flux to build up its voltage. At low values of field current the voltage varies proportionally, but as the field current increases, the steel portion of the magnetic circuit becomes partly saturated and the voltage increases more slowly.

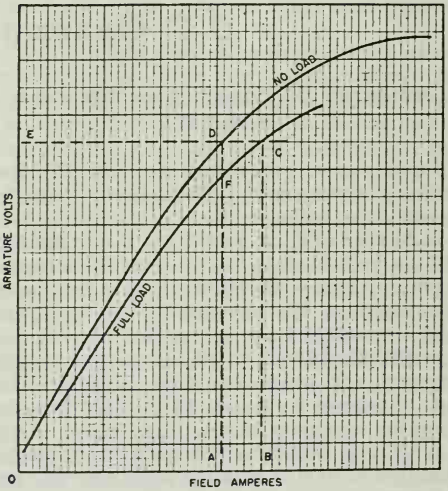


Figure 15-17.—Field saturation curves for d-c generator.

The abrupt bend in the curve is called the KNEE of the curve. Shunt generators are designed to operate at a point slightly above the knee so that a slight change in speed does not cause a great change in voltage. Compound generators operate at a lower point in order to avoid the use of a large series field winding.

SHUNT GENERATOR

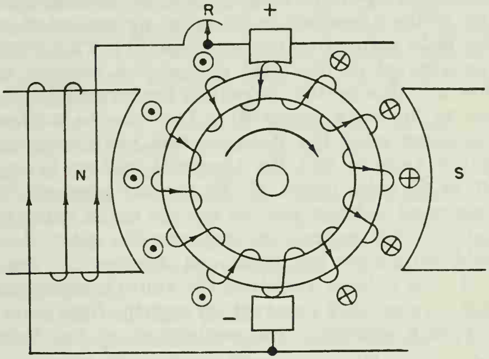
The shunt generator (fig. 15-16 (B)) has field coils of many turns of small size wire connected in shunt with the armature and load. The armature current is equal to the sum of the field current and the load current. The field current is small compared with the load current and is approximately constant for normal variations in load. Thus, the armature current varies directly with the load. The field flux produced by the field current is normally constant so that the terminal voltage does not vary widely with load change. Hence, the generator is essentially a constant-potential machine that delivers current to the load in accordance with the load demand.

Build Up of Voltage

After the generator is brought up to normal speed, and before any load is connected across the armature, the generator must ‘‘buildup’’ its voltage to the rated value (fig. 15-18). A schematic wiring diagram (fig. 15-18 (A)) is shown without load, and with only a few turns of the field coil around one pole indicated for simplicity in tracing the direction of current flow and the polarity of the voltage generated in the armature winding.

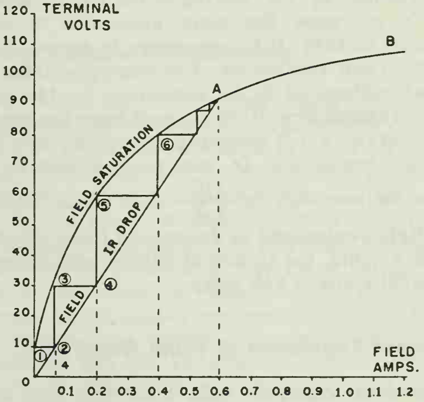
Figure 15-18 (B) indicates the field saturation curve for the generator. Line *OA* represents the relation between voltage and current in the field-coil circuit for one value of field-circuit resistance. Line *OA* is called an *IR*-drop curve for the field circuit and is assumed to be a straight line on the basis of constant temperature operation. The field rheostat permits adjustment of the field current through a relatively wide range and is designed so that its resistance is at least equal to that of the field winding.

At start, the generator is brought up to rated speed. The load is not connected. The armature conductors cut the small residual field and generate about 10 volts across the brushes (point ① on the saturation curve). The left-hand rule for generator action indicates that the generated voltage is applied to the field winding in a direction to supplement the residual field. Ten volts applied across the field circuit will cause approximately 0.07 ampere to flow through the field coils (point ② on the *IR*-drop curve).



SCHEMATIC WIRING DIAGRAM

(A)



FIELD SATURATION AND IR DROP CURVE

(B)

Figure 15-18.—Buildup of voltage of a shunt generator.

This current strengthens the field, and the armature voltage increases to 30 volts, as shown on the field saturation curve (point ③). During the process of voltage buildup the effect of the armature circuit resistance on the terminal voltage is neglected since the field current is only a small fraction of an ampere. This current flows through the armature and the accompanying *IR* drop is negligible. A generated voltage of 30 volts applied to the field circuit causes a field current of 0.2 ampere to flow, as shown by the *IR*-drop curve (point ④). This current in turn increases the field strength and generated voltage in the armature to 60 volts, as indicated on the field saturation curve (point ⑤). This voltage applied to the field causes 0.4 ampere to flow and this action increases the terminal voltage to 80 volts (point ⑥). The rise in voltage continues until the field current has increased to 0.6 ampere and the terminal voltage levels off at 90 volts (point *A*). No further increase in generated voltage occurs for the given value of field circuit resistance because the amount of field saturation flux produced is enough to generate the voltage required (90 volts) to circulate this current (0.6 ampere) through the field coils. For this condition the resistance of the field circuit is $\frac{90}{0.6}$, or 150 ohms. Field saturation limits the generated voltage to this value as determined by the setting of the field rheostat.

To increase the shunt generator terminal voltage further, it is necessary to decrease the field circuit resistance. For example, if the terminal voltage is to be increased to 110 volts, the corresponding field current from the saturation curve is 1.2 amperes (point *B*). The field circuit resistance is now represented by the slope of line *OB*, or $\frac{110}{1.2} = 91.8$ ohms. Thus, if the field resistance is decreased from 150 ohms to 91.8 ohms, the terminal voltage will increase from 90 volts to 110 volts.

Inherent Regulation of Shunt Generator

Internal changes, both electrical and magnetic, that occur in a generator automatically with load change, give the generator certain typical characteristics by which it may be identified. These internal changes are referred to as the inherent regulation of a generator. At no load, the armature current is equal to the field current. With low armature resistance and low field current there is little armature *IR* drop, and the generated voltage is equal to the terminal voltage. With load applied, the armature *IR* drop increases, but is relatively small compared with the generated voltage. Also the armature reaction voltage loss is small. Therefore, the terminal voltage decreases only slightly provided the speed is maintained at the rated value.

Load is added to a shunt generator by increasing the number of parallel paths across the generator terminals. This action reduces the total load circuit resistance with increased load. Since the terminal voltage is approximately constant, armature current increases directly with the load. Since the shunt field is in a separate circuit it receives only a slightly reduced voltage and its current does not change to any great extent.

Thus, with low armature resistance and a relatively strong field there is only a small variation in terminal voltage between no load and full load.

External Voltage Characteristics

A graph of the variation in terminal voltage with load on a shunt generator is shown in curve *A* of figure 15-19. This curve shows that the terminal voltage of a shunt generator falls slightly with increase in load from the no-load condition to the full-load condition. It also shows that with heavy overload the terminal voltage falls more rapidly. The shunt field current is reduced and the magnetization of the field falls to a low value. The dotted portion of curve *A* indicates the way the terminal voltage falls beyond the breakdown point. In large generators the breakdown point occurs at several times rated load current. Generators are not designed to be operated at these large values of load current and will overheat dangerously even at twice the value of full-load current.

Curve *B* represents the external voltage characteristic of a shunt generator with constant field current for variations in load between zero and approximately 25 percent over the rated load condition. Curve *C* represents the external voltage characteristic for the same range of load with simulated conditions of zero armature reaction and constant field current. The divergence of curve *C* from curve *D* represents the voltage variators resulting from the *IR* drop in the armature circuit. As mentioned previously, the terminal voltage of the shunt generator is prevented from varying widely with load change by providing it with a (1) low armature resistance, (2) strong main field with low armature reaction, and (3) separate field circuit in shunt with the armature and load.

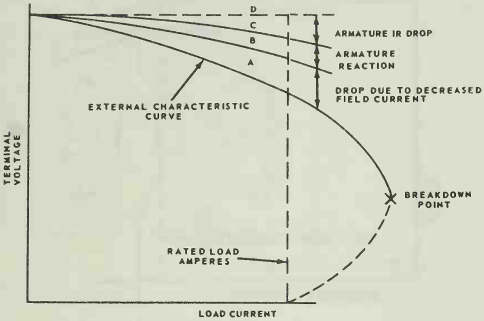


Figure 15-19.—Shunt generator external characteristics.

COMPOUND GENERATOR

Compound generators employ a series field winding in addition to the shunt field winding, as shown in figure 15-16 (B). The series field coils are made of a relatively small number of turns of large copper conductor, either circular or rectangular in cross section, and are connected in series with the armature circuit. These coils are mounted on the same poles on which the shunt field coils are mounted and therefore contribute a magnetomotive force that influences the main field flux of the generator.

Effect of Series Field

If the ampere-turns of the series field act in the same direction as those of the shunt field the combined magnetomotive force is equal to the sum of the series and shunt field components. Load is added to a compound generator in the same manner in which load is added to a shunt generator—by increasing the number of parallel paths across the generator terminals. Thus, the decrease in total load resistance with added load is accompanied by an increase in armature-circuit and series-field circuit current.

The effect of the additive series field is that of increased field flux with increased load. The extent of the increased field flux depends on the degree of saturation of the field iron as determined by the shunt field current. Thus, the terminal voltage of the generator may increase with load or it may decrease depending upon the influence of the series field coils. This influence is referred to as the degree of compounding.

For example, a FLAT-COMPOUND generator is one in which the no-load and full-load voltages have the same value. An UNDER-COMPOUND generator is one in which the full-load voltage is less than the no-load value. An OVER-COMPOUND generator is one in which the full-load voltage is higher than the no-load value. The way the terminal voltage changes with increasing load depends upon the degree of compounding.

A variable shunt is connected across the series field coils to permit adjustment of the degree of compounding. This shunt is called a DIVERTER. Decreasing the diverter resistance increases the amount of armature circuit current that is bypassed around the series field coils, thereby reducing the degree of compounding.

A field rheostat in the shunt field coil circuit permits adjustment of the no-load voltage of the compound generator. The diverter across the series field coils permits adjustment of the full-load voltage.

External Voltage Characteristics

The variation of terminal voltage with load is indicated in the external characteristic curves of figure 15-20. Curve *A* is the graph of terminal voltage versus armature current for a flat-compound generator. The no-load and full-load voltages are the same. Neither the diverter nor the field rheostat are altered in this test. The speed is maintained constant at the rated value. The hump in the curve is caused by the increased influence of the series ampere-turns on the field iron at half-load when the degree of saturation is reduced and the armature reaction and armature IR drop are approximately half their normal values.

Curve *B* is the external characteristic of an over-compound generator. As load is added to this machine its terminal voltage increases so that the field load voltage is higher than the no-load value. Such a characteristic might be desirable where the generator is located some distance from the load and the rise in voltage compensates for the voltage loss in the feeder. This action holds the load voltage approximately constant from no-load to full-load by increasing the generator terminal voltage an amount that is just equal to the voltage drop in the feeder at full load.

Curve *C* represents the external characteristic for an under-compound generator. The Navy uses a so-called stabilized shunt generator that has a small series field winding of a few turns in the coils to partially compensate for the voltage loss due to armature *IR* drop and armature reaction. Thus, the external characteristic is almost the same as that of a shunt generator except that the terminal voltage does not fall off quite as rapidly with increased load.

The stabilized shunt generator is the only type of compound generator commonly used in the Navy. This generator is used to supply general lighting and power aboard ship.

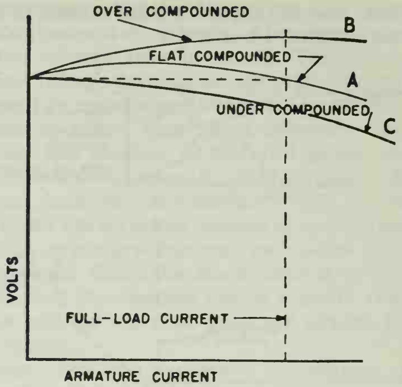


Figure 15-20.—Compound generator external characteristics.

Voltage Regulation

The external characteristic of a generator is sometimes called the VOLTAGE-REGULATION CURVE of the machine. The regulation of a generator refers to the VOLTAGE CHANGE that takes place when the load is changed. It is usually expressed as the change in voltage from no-load to full-load voltage in percent of full-load voltage. Expressed as a formula,

$$\frac{E_{nL} - E_{fL}}{E_{fL}} \times 100 = \text{percent regulation},$$

where E_{nL} is the no-load terminal voltage and E_{fL} is the full-load terminal voltage of the generator. For example, the percent regulation of a generator having a no-load voltage of 237 volts and a full-load voltage of 230 volts is

$$\frac{237 - 230}{230} \times 100, \text{ or } 3 \text{ percent.}$$

VOLTAGE CONTROL

Flat-compound generators were formerly used to supply the ship's d-c electric power because they provided a more constant voltage under varying load conditions. Shunt generators are simpler in design and have greater reliability when operating in parallel. The stabilized shunt generator represents a compromise between the two types. As mentioned previously, it has a very light series winding and a slightly drooping voltage characteristic and is generally used to supply the ship's d-c electric power requirements.

Voltage control is either (1) manual or (2) automatic. In most cases the process involves changing the resistance of the field circuit. By changing field circuit resistance, field current is controlled. Controlling field current permits control of the terminal voltage. Thus, the major difference between various voltage regulator systems is merely the method by which field circuit resistance and current are controlled. When the load changes are infrequent and small, manual control is sufficient to hold the d-c system voltage to the desired value. When the load changes are frequent and large, it may be desirable to employ some form of automatic control.

Inherent voltage regulation should not be confused with voltage control. As described previously, voltage regulation is an internal action occurring within the generator whenever the load changes. Voltage control is a super-imposed action usually by external adjustment. Certain electromechanical devices are used extensively in automatic voltage regulators. These include solenoids, relays, carbon piles, rocking disks, and tilted plates.

Manual Operation

A hand-operated field rheostat (fig. 15-21) connected in series with the shunt field circuit provides the simplest method of controlling the terminal voltage of a d-c generator.

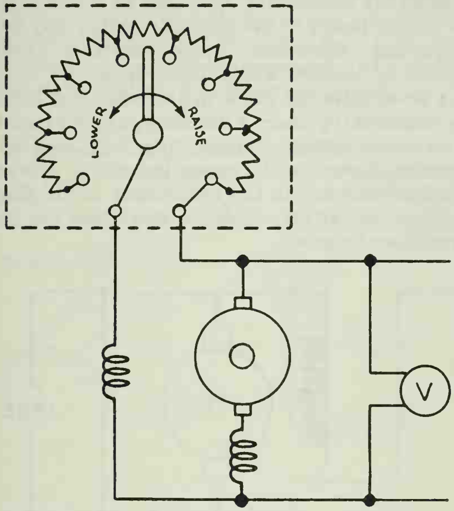


Figure 15-21.—Hand-operated field rheostat.

One form of field rheostat contains tapped resistors with leads to a multiterminal switch. The arm of the switch may be rotated through an arc to make contact with the various resistor taps, thereby varying the amount of resistance in the field circuit. Rotating the arm in the direction of the LOWER arrow increases the resistance and lowers the terminal voltage. Rotating the arm in the direction of the RAISE arrow, decreases the resistance and increases the terminal voltage.

Field rheostats for generators of moderate size employ resistors of alloy wire having a high specific resistance and a low temperature coefficient. These alloys include copper, nickel, manganese, and chromium and are marketed under trade names such as nichrome, advance, manganin, and so forth. Large generator field rheostats use cast-iron grids and a motor-operated switching mechanism.

Automatic Operation

Several types of automatic voltage regulators are used to control the terminal voltage of d-c generators. One of the earliest types was the vibrating regulator. More recent types include the tilted plate regulator and the rocking disk regulator.

The VIBRATING REGULATOR operates on the principle that an intermittent short circuit applied across the generator field rheostat will cause the terminal voltage of the generator to pulsate within narrow voltage limits and thus it will maintain an average steady value of voltage that is independent of load change. A simplified circuit is shown in figure 15-22.

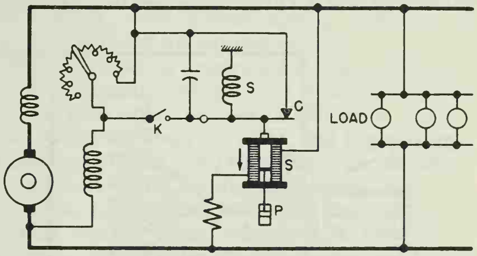


Figure 15-22.—Vibrating type of voltage regulator.

With the generator running at normal speed and switch *K* open, the field rheostat is adjusted so that the terminal voltage is about 60 percent of normal. Solenoid *S* is weak and contacts *C* are held closed by the spring. When *K* is closed, a short circuit is placed across the field rheostat. This action causes the field current to increase and the terminal voltage to rise.

When the terminal voltage rises above a certain critical value, for example 111 volts, the solenoid downward pull exceeds the spring tension and contact *C* opens, thus reinserting the field rheostat in the field circuit and reducing the field current and terminal voltage.

When the terminal voltage falls below a certain critical voltage, for example 109 volts, the solenoid armature contact *C* is closed again by the spring. The field rheostat is now shorted and the terminal voltage starts to rise. The cycle repeats and the action is rapid and continuous. The average voltage of 110 volts is maintained with or without load change.

The dashpot, *P*, provides smoother operation by acting as a damper to prevent hunting. The capacitor across contacts *C* eliminates sparking. Added load causes the field rheostat to be shorted for a longer period of time and thus the solenoid armature vibrates more slowly. If the load is reduced and the terminal voltage tends to rise, the armature vibrates more rapidly. Thus the regulator holds the terminal voltage to a steady value for any change in load from no load to full load on the generator.

The TILTED PLATE REGULATOR (fig. 15-23) consists of two or more stacks of graphite plates mounted on metallic supports at the center of each stack. Each plate is balanced on its fulcrum (the metallic support) at the center. On one end of the stack the plates are separated by mica spacers. On the other end they are separated by silver contacts. Before the silver contacts are closed, the path for field circuit current is from graphite plate to graphite plate through the connecting fulcrums at the center of the stack. Between the graphite plates and their supporting fulcrums there exists a certain amount of contact resistance. A weight acting on a lever tilts the plate in a manner that brings the contacts together. A solenoid, which responds to terminal voltage change, tilts the plates in the opposite direction. Bringing the silver contacts together shorts out the resistance of the stack. Opening the silver contacts increases the field circuit resistance.

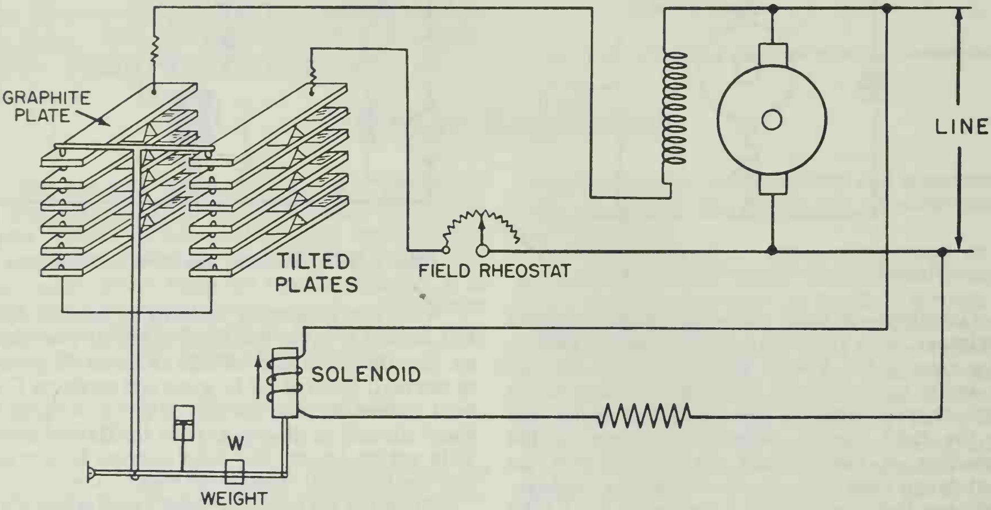


Figure 15-23.—Tilted plate voltage regulator.

The regulator responds to load change and is not designed to overshoot in the manner of the vibrating regulator previously described. For example, at rated voltage the solenoid is in balance with the lever weight and the arm does not move. An increase in load decreases the terminal voltage only slightly because the lever weight immediately overcomes the solenoid and tilts the plates in a direction to lower the resistance, thereby strengthening the field and the generated voltage. This action checks the fall of terminal voltage with load.

The ROCKING DISK REGULATOR (fig. 15-24) is another device that is quick acting and sensitive to slight changes in terminal voltage. It may be designed to be in a constant-motion condition of overshooting the voltage a slight amount through each cycle of operation or it may be operated in a static condition in which load change alone causes it to operate.

A spring presses the rocking disk against the flat surface of a silver-plated commutator, the segments of which connect to taps on the field circuit resistors. The disk has a carbon shoe which makes contact with the segments one at a time from top to bottom as the disk is rocked downward. A small range of motion of the spring is converted into a long range of motion of the contact point of the carbon shoe with the various commutator segments. The lever weight tends to rock the disk downward. The solenoid tends to rock the disk upward. For a constant load on the generator, the lever weight and the solenoid are in a state of balance. Thus, the shoe is in contact with one commutator segment, and a portion of the field resistors is short-circuited.

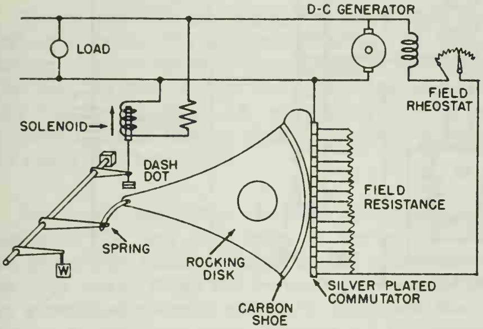


Figure 15-24.—Rocking disk voltage regulator.

When the load on the generator increases, the terminal voltage of the generator starts to fall. The solenoid is weakened and the weight rocks the disk downward, thus short-circuiting more of the field resistors and increasing the generated voltage. The decrease in terminal voltage is almost instantly checked by the increase in field strength and generated voltage, and the weight is now in balance with the solenoid at a new position where the disk contacts a commutator segment nearer the lower end of its travel.

A decrease in load causes the terminal voltage to start to rise and this strengthens the solenoid. Thus the disk rocks in an upward direction and more resistance is inserted in the field circuit, with accompanying decrease in field strength and generated voltage.

The decrease in generated voltage checks the rise in terminal voltage. For example, at one load the generated voltage is 120 volts, the internal voltage loss is 10 volts, and the terminal voltage is 120 - 10, or 110 volts. With decrease in load the internal voltage loss might decrease to 5 volts, and without automatic regulation the terminal voltage would increase to 120 - 5, or 115 volts. However, with automatic regulation the terminal voltage momentarily rises to 111 volts and the regulator causes the generated voltage to fall from 120 volts to 111 + 5, or 116 volts, and to become stable at 115 volts when the terminal voltage is again 115 - 5, or 110 volts.

Regulators for Variable-Speed Generators

VIBRATOR-TYPE REGULATOR

If the speed of a shunt generator varies the output voltage will vary. In cars, trucks, small boats, and some aircraft, the generator is usually driven from the main source of power, which may be a variable-speed internal-combustion engine. If the generator is of the shunt type, a 3-unit regulator is often employed. One unit consists of a vibrating voltage regulator that places an intermittent short-circuit across a resistor in series with the field. This action is similar to the vibrating-type voltage regulator described earlier in this chapter. The second unit is a current limiter that limits the output current to a value determined by the rating of the generator. The three-unit regulator (fig. 15-25) is designed for use in a power system employing a battery as an auxiliary power supply. The third unit in the regulator is a reverse-current cutout that prevents the battery from motorizing the generator at low speeds by disconnecting the battery from the generator. If the voltage of the generator falls below that of the battery, the battery will discharge through the generator armature; thereby tending to drive the generator as a motor. This action is called "motorizing" the generator, and unless it is prevented, will discharge the battery in a short time.

The action of vibrating contact $C1$ in the voltage-regulator unit (fig. 15-25) places an intermittent short circuit across $R1$ and $L2$. When the generator is not operating, spring $S1$ holds $C1$ closed. $C2$ is also closed by $S2$, and the shunt field is connected directly across the armature.

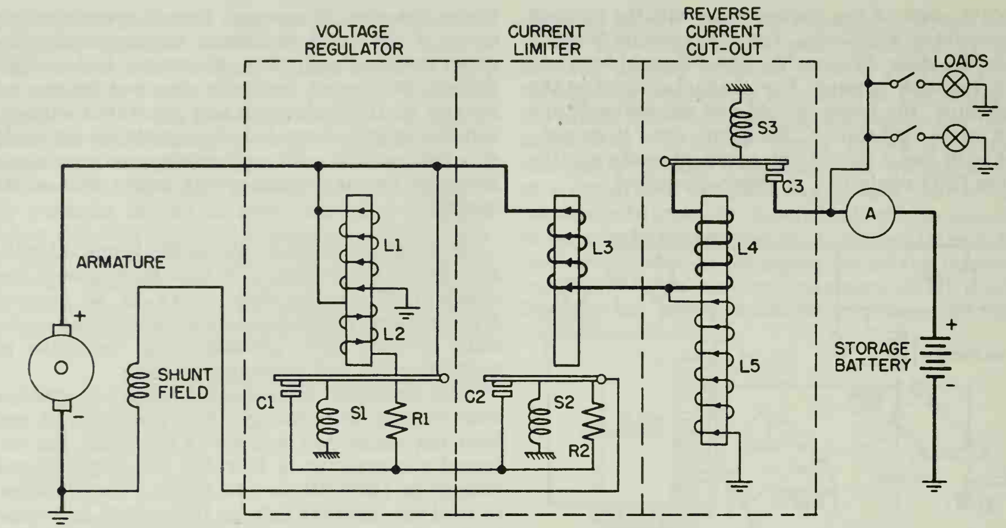


Figure 15-25.—Regulator for variable-speed generator.

When the generator is started, its terminal voltage will rise as the generator comes up to speed, and the armature will apply the field with current through closed contacts *C*2 and *C*1.

As the terminal voltage rises, the current flow through *L*1 increases and the iron becomes more strongly magnetized. At a certain speed and voltage, when the magnetic attraction on the movable arm becomes strong enough to overcome the tension of spring *S*1, contact points *C*1 are separated. The field current now flows through *R*1 and *L*2. Because resistance is added to the field circuit, the field is momentarily weakened and the rise in terminal voltage is checked. Additionally, because the *L*2 winding is opposed to the *L*1 winding, the magnetic pull of *L*1 against *S*1 is partially neutralized, and spring *S*1 closes contact *C*1. *R*1 and *L*2 are again shorted out of the circuit, the field current again increases, the output voltage increases, and *C*1 is opened because of the action of *L*1. The cycle of events occurs very rapidly, many times per second. The terminal voltage of the generator thus varies slightly but rapidly above and below an average value determined by the tension of spring *S*1, which may be adjusted.

The purpose of the vibrator-type current limiter is to limit the output current of the generator automatically to its maximum rated value in order to protect the generator. As shown in figure 15-25, *L*3 is in series with the main line and load. Thus, the amount of current flowing in the line determines when *C*2 will be opened and *R*2 placed in series with the generator field. By contrast, the voltage regulator is actuated by line voltage, whereas the current limiter is actuated by line current. Spring *S*2 holds contact *C*2 closed until the current through the main line and *L*3 exceeds a certain value, as determined by the tension of spring *S*2, and causes *C*2 to be opened. The increase in current is due to an increase in load. This action inserts R2 into the field circuit of the generator and decreases the field current and the generated voltage. When the generated voltage is decreased, the generator current is reduced. The core of *L*3 is partly demagnetized, and the spring closes the contact points. This causes the generator voltage and current to rise until the current reaches a value sufficient to start the cycle again. A certain minimum value of load current is necessary to cause the current limiter to vibrate.

The purpose of the reverse-current cutout relay (fig. 15-25) is to disconnect the battery automatically from the generator whenever the generator voltage is less than the battery voltage. If this device were not used in the generator circuit, an especially harmful action would occur if the engine were shut off. The battery would discharge through the generator. This would tend to make the generator operate as a motor, but because the generator is coupled to the engine it could not rotate such a heavy load. Under this condition, the generator winding may be severely damaged by excessive current.

There are two windings, *L*4 and *L*5, on the soft-iron core. The current winding, *L*4, consisting of a few turns of heavy wire, is in series with the line and carries the entire line current. The voltage winding, *L*5, consisting of a large number of turns of fine wire, is shunted across the generator terminals.

When the generator is not operating, the contacts, *C*3, are held open by spring *S*3. As the generator voltage builds up, *L*5 magnetizes the iron core. When the current (as a result of the generated voltage) produces sufficient magnetism in the iron core, contact *C*3 is closed, as shown. The battery then receives a charging current. The coil spring, *S*3, is so adjusted that the voltage winding will not close the contact points until the voltage of the generator is in excess of the normal voltage of the battery. The charging current passing through *L*4 aids the current in *L*5 in holding the contacts tightly closed. Unlike *C*1 and *C*2, contacts *C*3 do not vibrate. When the generator slows down, or for any other cause the generator voltage decreases to a certain value below that of the battery, the current reverses through *L*4 and the ampere-turns of *L*4 oppose those of *L*5. Thus, a momentary discharge current from the battery reduces the magnetism of the core and *C*3 is opened, thereby preventing the battery from discharging into the generator and motorizing it. *C*3 will not close again until the generator terminal voltage exceeds that of the battery by a predetermined value.

CARBON-PILE TYPE REGULATOR

The carbon-pile voltage regulator is the type most commonly used in naval aircraft. Its essential parts are shown in figure 15-26. A stack of carbon washers, the "pile," is in series with the shunt field. The resistance of the pile, and thus field current, depends on the mechanical pressure applied to the pile by the wafer spring which acts through the movable iron armature. In a steady-state condition, the magnetic force of the potential coil acts to pull the iron armature away from the pile. This force is balanced by the spring. When a change in line voltage occurs, due to a change in generator speed or load, the potential coil current also changes. Its magnetic strength must also change. As a result, the spring pressure on the carbon pile is INCREASED by a drop in line voltage, and DECREASED by a rise in line voltage. The resultant change in shunt field current will raise or lower the generator output voltage as needed. Variations in voltage characteristics from bench adjustment and aircraft installation may be adjusted by the rheostat, which controls the potential coil current.

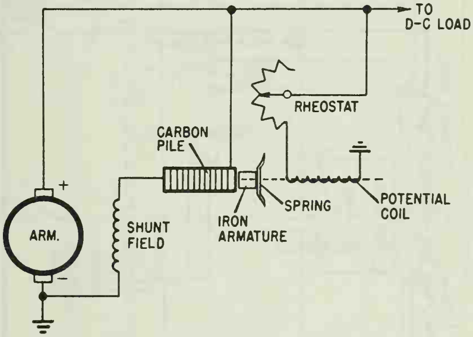


Figure 15-26.—Carbon-pile regulator.

Parallel Operation

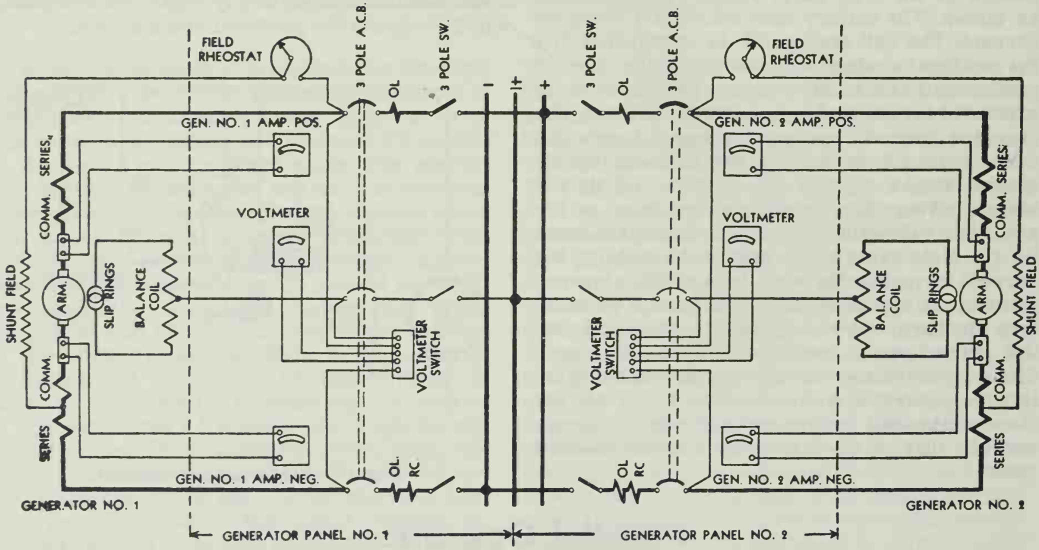
Electric power aboard ships may be supplied by more than one generator. When two or more generators are sharing a common load, they are said to be operating in parallel. The generators may be located in different parts of the ship, but are connected to the common load through the ship's power distribution system.

There are a number of reasons for operating generators in parallel. First, the number of generators used may be selected in accordance with the load demand. Thus, by operating each generator as near as possible at its rated capacity, maximum efficiency is achieved. Also, disabled or faulty generators may be taken off the line without interrupting normal operations.

In naval vessels that are provided with d-c electric power systems, the lighting circuits are designed to operate on 115 volts while most motors and other relatively large power-consuming devices are designed to operate on 230 volts. To avoid the use of separate generators for lighting and for power, a 3-wire generator is used that supplies both types of circuits simultaneously. The 3-wire generator is similar to a 2-wire generator except that the armature winding is tapped at points 180 electrical degrees (1-pole span) apart and these are brought out to slip rings on the back of the armature. These rings are connected by means of brushes to a reactance coil. The center tap of the coil connects with the neutral, or third, wire of the 3-wire system.

The reactance coil (or balance coil) provides a method of establishing the potential of the neutral wire, which must be 115 volts positive with respect to one of the outer wires and 115 volts negative with respect to the other. Alternating current is produced in the armature of the d-c generator; and this is taken from the machine through the sliprings to which the balance coil is attached. The action of the alternating current in the balance coil is similar to that occurring in the primary winding of a single-phase transformer. That is, the potential of the center point on the balance coil is at the electrical center of the total voltage generated by the machine. Hence, this point can serve as the neutral, or center, between the positive and negative brushes. The neutral current passes through a portion of the balance coil, which has low resistance to direct current.

The connections for operating stabilized shunt generators in parallel are shown in figure 15-27. Each generator develops 230 volts across the two outside (positive and negative) leads, and 115 volts across either outside leads and neutral. Usually one ammeter and one voltmeter are provided on each generator panel.


FIELD RHEOSTAT
3 POLE A.C.B.
OL
3 POLE SW.
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±
+
3 POLE SW.
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3 POLE A.C.B.
FIELD RHEOSTAT
GEN. NO. 1 AMP. POS.
GEN. NO. 2 AMP. POS.
SERIES
COMM.
SHUNT FIELD
ARM.
SLIP RINGS
BALANCE COIL
VOLTMETER
VOLTMETER SWITCH
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SERIES
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SHUNT FIELD
COMM.
SERIES
COMM.
SERIES
GEN. NO. 1 AMP. NEG.
OL
RC
OL
RC
GEN. NO. 2 AMP. NEG.
GENERATOR NO. 1
GENERATOR NO. 2
GENERATOR PANEL NO. 1
GENERATOR PANEL NO. 2

Figure 15-27.—Parallel operation of d-c generators.

Assume that generator No. 1 is supplying the load and it is desired to put generator No. 2 in service. The procedure for paralleling the d-c generators is as follows:

1. The brush rigging and armature of the incoming generator should be inspected for loose gear, and the field rheostat should be adjusted to the lowest voltage position.

2. The prime mover of the incoming generator (No. 2) is brought up to rated speed.

3. The voltage of the incoming machine is adjusted to about 2 volts higher than the bus voltage.

4. Closing the circuit breaker and switch places the generator in parallel with generator No. 1. The ammeter will indicate that generator No. 2 is now carrying a small portion of the load.

5. The field of generator No. 2 is strengthened until the load which it supplies is the proper value. At the same time the field of generator No. 1 should be weakened to maintain the normal voltage.

The procedure for removing a generator from its parallel connection with another is as follows:

1. The field of the generator being secured is weakened at the same time the field of the remaining generator is strengthened until the load on the outgoing machine is about 5 percent of the rated load current.

2. The circuit breaker is tripped and the switch is opened.

TWO-WIRE D-C SYSTEM

The two-wire d-c system is used for d-c power supply on naval aircraft. On multiengine aircraft, the d-c generators are normally operated in parallel. Figure 15-28 is a schematic of the main parts of a typical aircraft d-c power system. Both generators are connected to the main bus, or common load, through their respective reverse-current cutout relays.

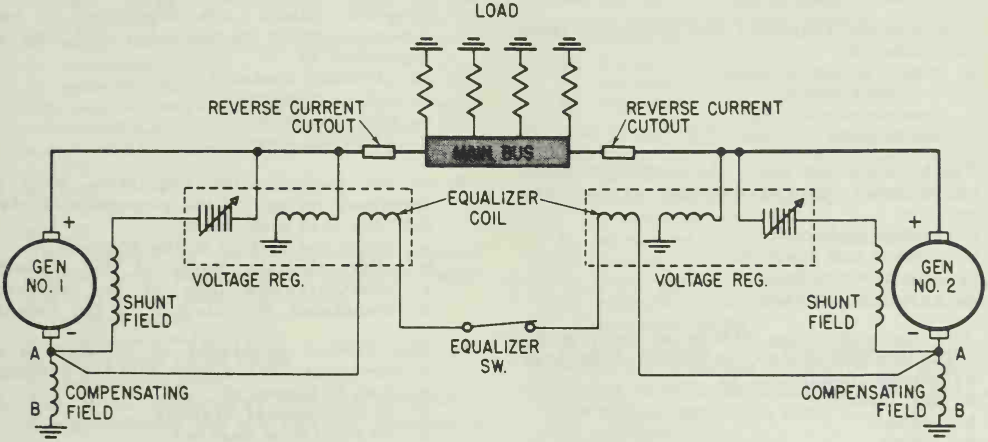


Figure 15-28.—Aircraft d-c power system.

The voltage regulators for aircraft d-c generators are designed and adjusted to permit a slight drooping characteristic. That is, the voltage regulators will permit the terminal voltage of their respective generators to decrease slightly as the bus load is increased. The amount of droop of two or more generators may not be equal, due to internal differences in the generators or adjustment of their regulators. In such cases, one generator will assume more load than the other, as loads are added to the bus.

To assure that the generators will carry equal loads, an automatic load balancing circuit is built into the regulator system. It is referred to as the equalizer. As shown in figure 15-28, the equalizer circuit consists essentially of two equalizer coils and an equalizer switch, all in series, connected between point A in generator No. 1 and point A on generator No. 2. Current through the equalizer circuit flows only when the voltage drops across the compensating fields A-B are unequal. This would be the case when the generators are supplying unequal shares of the total load. The equalizer coils either aid or oppose the regulator potential coils, depending on the DIRECTION of equalizer current. When one generator takes a greater share of the load than the other, the equalizer coil in its regulator will AID the potential coil. This will cause carbon pile decompression, more resistance and less current in the shunt field, less generated voltage, and consequently a decrease in load. The other generator's equalizer coil will OPPOSE its potential coil, increase its shunt field current, raise its generated voltage, and thus cause the generator to assume more of the load.

When only one generator is being operated, the equalizer switch is used to open the equalizer circuit. Otherwise, current would flow from the active generator through the dead generator's compensating field and equalizer coil.

QUIZ

1. A d-c generator is a rotating machine that converts
   a. electrical energy to mechanical energy
   b. mechanical energy to electrical energy
   c. low mechanical energy to a higher level of mechanical energy
   d. low electrical energy to a higher level of electrical energy
2. Commutator segments are insulated from each other by
   a. small strips of wood
   b. a rubber insert
   c. laminated varnish
   d. sheet mica
3. The brushes that carry the current from the commutator to the external circuit are made of
   a. carbon and lead
   b. carbon and graphite
   c. graphite and lead
   d. graphite and zinc
4. The heat-radiating ability of very small armature conductors, as compared to large armature conductors, is
   a. the same
   b. higher
   c. lower
   d. there is no relation
5. The degree that the neutral plane of a generator will shift under load is
   a. inversely proportional to the load
   b. proportional to the load
   c. always less than proportional to the load
   d. independent of the load
6. D-c generators are classified according to the manner in which
   a. they are used
   b. the field windings are connected to the load
   c. the armature circuit is connected to the load
   d. the field windings are connected to the armature circuit
7. The only type of compound generator commonly used in the Navy is the
   a. over compounded
   b. flat compounded
   c. stabilized shunt
   d. cumulative compounded
8. On one end of the tilted plate regulator the graphite plates are separated by mica spacers, while on the other end they are separated by
   a. platinum contacts
   b. silver contacts
   c. zinc contacts
   d. a carbon shoe
9. In the rocking disk regulator, when the terminal voltage of the generator starts to fall, the disk movement
   a. opens the circuit to the solenoid
   b. short-circuits more of the resistors
   c. short-circuits less of the resistors
   d. completes the circuit to the solenoid
10. The 3-wire generator is similar to the 2-wire generator except that the armature winding is tapped at
    a. 30 mechanical degrees
    b. 90 electrical degrees
    c. 180 electrical degrees
    d. 30 electrical degrees
11. The name given to the mechanical power source used to turn the armature of a d-c generator is the
    a. motor driver
    b. machine driver
    c. prime mover
    d. rotor
12. Flashover between the commutator segments in a high-voltage d-c generator is prevented by
    a. reducing the number of segments
    b. increasing the number of segments
    c. reducing the number of field coils
    d. increasing the number of field coils

13. The distance between the two sides of a coil in a d-c generator armature is called
    a. coil pitch
    b. commutator pitch
    c. pole span
    d. pole pitch
14. The effects of armature reaction in a generator are reduced by the use of
    a. commutating windings
    b. interpoles
    c. commutating windings and interpoles
    d. compensating windings and commutating poles
15. The need for shifting the brushes of a d-c generator as its load changes has been eliminated by the use of
    a. interpoles
    b. commutating poles
    c. compensating windings
    d. larger brushes
16. A shunt generator will build up to full terminal voltage with no external load connected to it due to
    a. the large conductors used in the armature
    b. motor action of the generator
    c. interpoles
    d. self-excitation
17. The percent regulation of a generator having a no-load e.m.f. of 220 volts and a full-load e.m.f. of 215 volts is approximately
    a. 3%
    b. 45%
    c. 0.02%
    d. 2%
18. The purpose of the vibrator-type current limiter is to automatically limit the output current of the generator to its
    a. preset value
    b. minimum rated value
    c. maximum rated value
    d. saturation point
19. The main differences between shipboard d-c generators and aircraft d-c generators are
    a. size, rating, and appearance
    b. size, appearance, and function
    c. size and rating only
    d. appearance, rating, and function
20. The part of a d-c generator into which the working voltage is induced is the
    a. yoke
    b. field poles
    c. armature
    d. commutator
21. Power lost in heat in the windings due to the flow of current through the copper is known as
    a. eddy current loss
    b. hysteresis loss
    c. copper loss
    d. none are correct
22. Compensating windings are imbedded in the pole faces parallel to the armature conductors and are electrically connected with the armature windings in
    a. parallel
    b. series-parallel
    c. series
    d. numbers equal to the number of armature conductors
23. As armature current of a generator increases, motor reaction force
    a. decreases
    b. remains the same
    c. increases
    d. has no relation to armature current
24. The small variable shunt connected across the series field coils, to permit adjustment of the degree of compounding, is a
    a. diverter
    b. divider
    c. resistor
    d. rheostat
25. The major difference between various voltage regulator systems is merely the method by which
    a. field circuit resistance and current are controlled
    b. armature circuit resistance is controlled
    c. load circuit resistance is controlled
    d. armature current and load resistance are controlled
26. In the rocking disk regulator (fig. 15-24), when the terminal voltage of the generator starts to fall, the solenoid is weakened and the weight rocks the disk
    a. upward
    b. to the left
    c. to the right
    d. downward
27. In the carbon-pile type regulator, the mechanical pressure on the carbon pile is applied by the
    a. wafer spring
    b. potential coil
    c. iron core of the potential coil
    d. rheostat

CHAPTER 16

DIRECT-CURRENT MOTORS

The construction of a d-c motor is essentially the same as that of a d-c generator. The d-c generator converts mechanical energy into electrical energy, and the d-c motor converts the electrical energy back into mechanical energy. A d-c generator may be made to function as a motor by applying a suitable source of direct voltage across the normal output electrical terminals.

There are various types of d-c motors, depending on the way the field coils are connected. Each has characteristics that are advantageous under given load conditions.

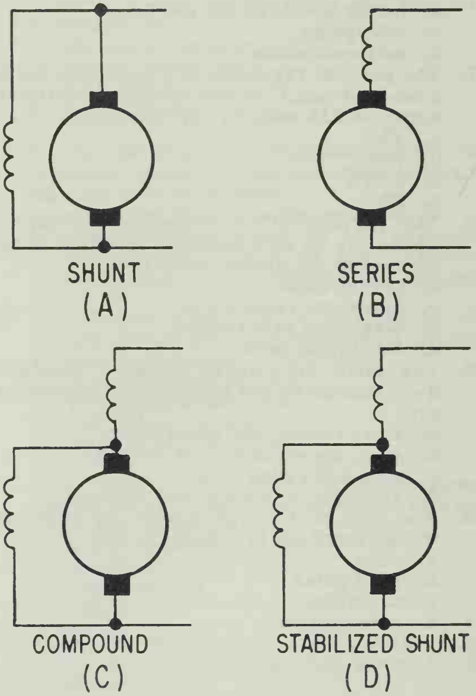
SHUNT MOTORS have the field coils connected in parallel with the armature circuit. This type of motor, with constant potential applied, develops variable torque at an essentially constant speed, even under changing load conditions. Such loads are found in machineshop drives. They include lathes, milling machines, drills, planers, shapers, and so forth.

SERIES MOTORS have the field coils connected in series with the armature circuit. This type of motor, with constant potential applied, develops variable torque but its speed varies widely under changing load conditions. That is, the speed is low under heavy loads, but becomes excessively high under light loads. Series motors are commonly used to drive electric cranes, hoists, winches, and certain types of vehicles (for example, electric trucks). Series motors are used extensively to start internal combustion engines.

COMPOUND MOTORS have one set of field coils in parallel with the armature circuit, and another set of field coils in series with the armature circuit. This type of motor is a compromise between shunt and series motors. It develops an increased starting torque over that of the shunt motor, and has less variation in speed than the series motor. Shunt, series, and compound motors are all d-c motors designed to operate from constant-potential variable-current d-c sources.

STABILIZED SHUNT MOTORS have a light series winding in addition to the shunt field. The action is similar to ordinary shunt motors except that stabilized shunt motors have less field iron and are lighter in weight. Without the stabilizing series field, they have the characteristics of a shunt motor with a strong field and low armature resistance.

Schematic diagrams of the four basic types of d-c motors are shown in figure 16-1.


SHUNT (A)

SERIES (B)

COMPOUND (C)

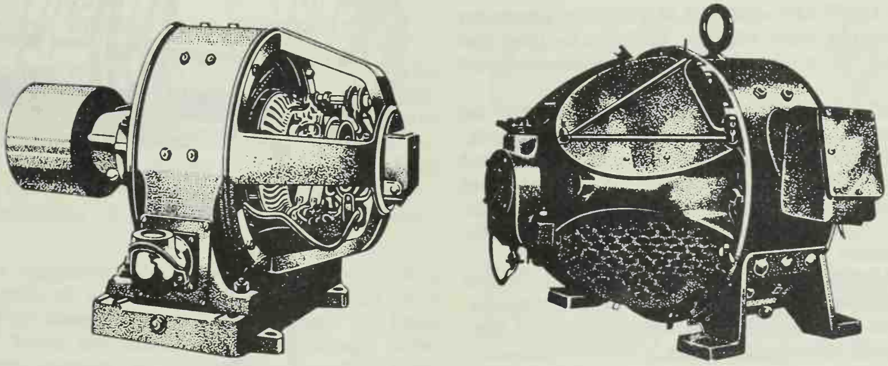
STABILIZED SHUNT (D)

Figure 16-1.—Schematic diagrams of four types of d-c motors.

Direct-current motors may also be classified in other ways. For example, they may be classified according to the degree of enclosure, such as OPEN (fig. 16-2 (A)), DRIP-PROOF (fig. 16-2 (B)), ENCLOSED (fig. 16-2 (C)), and so forth.

The open-type motor shown in figure 16-2 (A) has end bells which offer little or no restriction to ventilation. The drip-proof motor shown in figure 16-2 (B) is protected from falling moisture and dirt from any direction up to a 45° angle with respect to the vertical. A motor of this type has all ventilation openings protected with wire screens or perforated covers, as shown in the figure. An enclosed motor like the one in figure 16-2 (C) is totally enclosed except for openings provided for the admission and discharge of air. These openings are connected to inlet and outlet ducts or pipes.

Other motor types include a spray-tight motor so constructed that a stream of water from a hose may be played upon it from any direction without leakage into the motor.


OPEN-TYPE MOTOR
(A)

DRIP-PROOF MOTOR
(B)

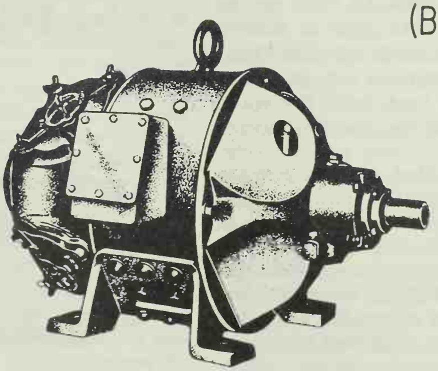

ENCLOSED MOTOR
(C)

Figure 16-2.—Types of shipboard d-c motors classified according to enclosure.

A submersible motor is one that will operate while submerged in liquid.

With reference to cooling, the following types of motors are found aboard ship:

1. NATURAL VENTILATED MOTORS, cooled by the natural circulation of the air caused by the rotation of the armature.
2. SELF-VENTILATED MOTORS, cooled by a fan attached to the armature of the motor.
3. SEPARATELY VENTILATED MOTORS, cooled by an independent fan or blower apart from the motor.

With reference to speed, motors are classified as:

1. CONSTANT-SPEED MOTORS in which the speed varies only slightly between no load and full load. A shunt motor is a constant-speed motor.
2. MULTISPEED MOTORS which can be operated at any one of several definite speeds, each speed being nearly constant with load change. Such motors cannot be operated at intermediate speeds. A motor with two windings on the armature is an example of a multispeed motor.
3. ADJUSTABLE-SPEED MOTORS whose speed can be varied gradually over a wide range, but when once adjusted remains at nearly constant speed with load change.
4. VARYING SPEED MOTORS in which the speed varies with the load. Ordinarily the speed decreases as the load increases. The series motor is an example of this type of motor.
5. ADJUSTABLE VARYING SPEED MOTORS in which the speed may be adjusted over a wide range for any given load; but if the speed is adjusted at a given load, the speed will vary with any change in load.

Motors are also classified according to the type of duty they are to perform. For example, a CONTINUOUS-DUTY MOTOR is capable of operating continuously at its rated output without exceeding specified temperature limits. An INTERMITTENT-DUTY MOTOR is capable of being operated at its rated output for a limited period without exceeding its specified temperature limit.

Most d-c motors on Navy vessels are designed to operate on constant-potential 2-wire circuits of either 115 volts or 230 volts. These circuits may be combined in a 3-wire d-c supply with 230 volts between each outside wire, and 115 volts between each outside wire and middle or neutral wire.

D-c motors find extensive use on naval aircraft. The motors used on aircraft operate on the same principles as the larger motors aboard ship. However, the airborne motors differ considerably in size, rating, and appearance, as illustrated in figure 16-3. Also, they are designed to operate from a 24-28 volt d-c source.

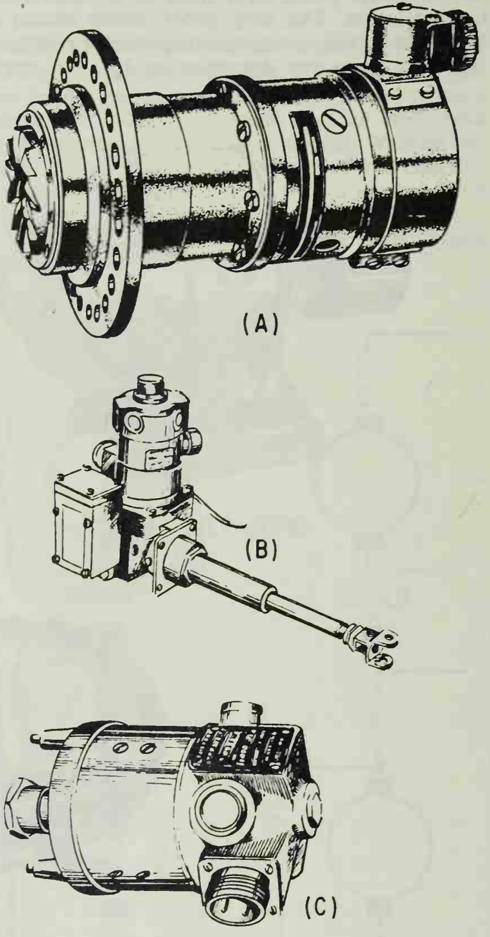


Figure 16-3.—Aircraft d-c motors.

Part (A) is an aircraft engine starter motor. Starters are series motors, selected to supply the typically high torque required for engine starting. They are usually the largest motors on the aircraft, with power outputs up to twenty h.p., but are designed only for intermittent use. Part (B) is one of many types of d-c motors used to actuate mechanical loads, in this case cowl flaps. Such loads may include wing flaps, cowl flaps, landing gear, cockpit canopies, and bomb bay doors. Actuator motors are also of the series type, since they must start under full mechanical load. Many airborne actuator motors are of the series split-field type, and are reversible. Most are also designed only for intermittent use. Part (C) is a continuous-duty d-c motor, in this case one that is used to drive windshield wipers. Continuous-duty motors on aircraft are usually of the compound type. The most recent trend in aircraft design is to use d-c motors for intermittent duty, and a-c motors for continuous duty.

Principles of D-C Motors

FORCE ACTING ON A CONDUCTOR

The operation of a d-c motor depends on the principle that a current-carrying conductor placed in, and at right angles to, a magnetic field tends to move at right angles to the direction of the field, as shown in figure 16-4. This action was previously described under the operating principle of the D'Arsonval meter movement.

The magnetic field between a north and a south pole of a magnet is shown in figure 16-4 (A). The lines of force, comprising the field extend from the north pole to the south pole. A cross section of a current-carrying conductor is shown in figure 16-4 (B). The plus sign in the wire indicates that the electron flow is away from the observer. The direction of the flux loops around the wire is counterclockwise, as shown. This follows from the left-hand flux rule which states that if the conductor is grasped in the left hand with the thumb extended in the direction of the current flow, the fingers will curve around the conductor in the direction of the magnetic flux.

If the conductor (carrying the electron flow away from the observer) is placed between the poles of the magnet, as in figure 16-4 (C), both fields will be distorted. Above the wire the field is weakened, and the conductor tends to move upward. The force exerted upward depends on the strength of the field between the poles and on the strength of the current flowing through the wire.

If the current through the conductor is reversed, as in figure 16-4 (D), the direction of the flux around the wire is reversed. The field below the conductor is now weakened, and the conductor tends to move downward.

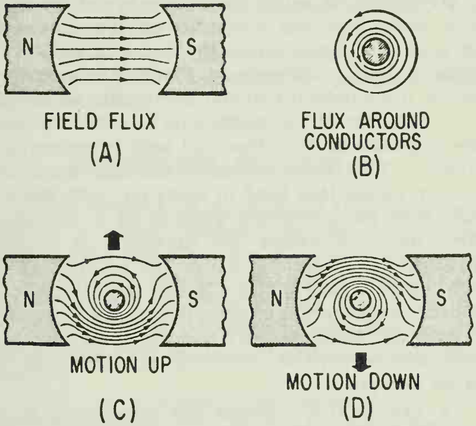
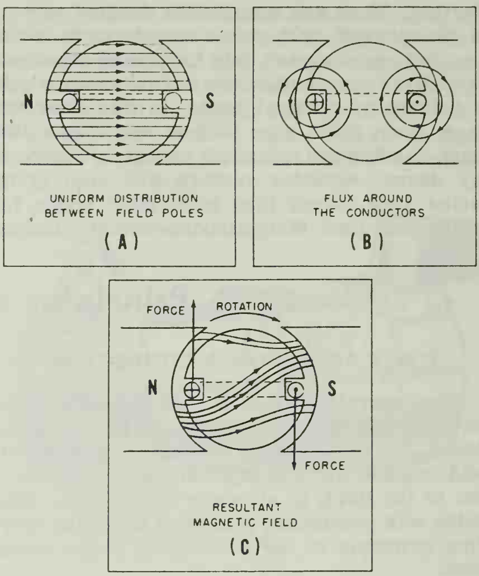


Figure 16-4.—Force acting on a current-carrying conductor in a magnetic field.

A convenient method of determining the direction of motion of a current-carrying conductor in a magnetic field is by the use of the right-hand motor rule. Practical d-c motors depend for their operation on the interaction between the field flux and a large number of current-carrying conductors. As in d-c generators, the conductors are wound in slots in the armature; and the armature is mounted in bearings and is free to rotate in the magnetic field. An armature with two slots and two conductors (that is, a single conductor wound in the two slots) is shown in figure 16-5.

Figure 16-5 (A) shows the uniform distribution of the main field flux when the field magnets are energized, and no current flows through the armature. The flux is concentrated in the air gap between the field and armature because of the relatively high permeability of the soft-iron armature core and the low reluctance of the magnetic circuit.



UNIFORM DISTRIBUTION BETWEEN FIELD POLES

(A)

FLUX AROUND THE CONDUCTORS

(B)

RESULTANT MAGNETIC FIELD

(C)

Figure 16-5.—Two-conductor armature.

Figure 16-5 (B) shows the magnetic fields surrounding the two active conductors when current flows through the armature coil in the direction indicated, and the field coils are not energized. The direction of the magnetic fields surrounding the two conductors is determined by means of the left-hand flux rule.

Figure 16-5 (C) shows the resultant magnetic field produced by the interaction of the main field magnetomotive force and the armature magnetomotive force. Note that the flux is strengthened below the conductor at the north pole and above the conductor at the south pole because the lines are in the same directions at these points. Conversely, the flux is weakened above the conductor at the north pole and below the conductor at the south pole because the lines are opposite in direction and tend to cancel each other. The lines of force act like stretched rubber bands that tend to contract, with the result that the armature rotates in a clockwise direction. If either the direction of current through the armature coil or the polarity of the field is reversed (but not both), the direction of the force on the armature conductors reverses. If both the field polarity and the armature current are reversed, rotation continues in the same direction.

A practical d-c motor has many coils in the armature winding. The armature has many slots into which are inserted many turns of wire. This increases the number of armature conductors and thus produces a greater, more constant torque. Power output is also increased by increasing the number of poles in the field.

As in the case of the d-c generator, the d-c motor is equipped with a commutator and brushes.

The force, F, acting on a current-carrying conductor in a magnetic field is directly proportional to the field strength, the active length of the conductor (that part of the conductor contained in the armature slot and lying under a pole face), and the current flowing through it. The force, the conductor, and the field are assumed to be mutually perpendicular. This relationship is expressed algebraically as

$$F = \frac{8.85 \times BLI}{10^8},$$

where F is the force in pounds, B the flux density in lines per square inch, L the active length of the conductor in inches, I the current in amperes flowing through the conductor, and 8.85 is a constant that must be used when the above units are employed.

In a given motor, the length of the conductor is a fixed quantity: therefore, the only variables are the current and the flux. If the field flux is constant, the force acting on the conductor varies directly as the armature current. In other words, F is proportional to I. The following example will illustrate how the force acting on a conductor is calculated.

If a conductor having an active length of 10 inches and a current of 30 amperes is placed in a uniform field of 37,700 lines per square inch, what force will be exerted on the conductor?

$$F = \frac{8.85\ BLI}{10^8} = \frac{8.85 \times 37{,}700 \times 10 \times 30}{10^8} = 1 \text{ pound.}$$

If the conductor is wound around an armature (fig. 16-5 (C)) and the armature current flows in the directions shown, there will be an upward force of one pound on the left of the armature and a downward force of one pound on the right of the armature. The net force acting to turn the armature is the sum of these two forces, or two pounds.

TORQUE

The TORQUE (or twist) on the armature is the product of the force acting at the surface of the armature times the perpendicular distance to the center of rotation of the armature. Assume the radius of the armature being considered is 1.5 feet, the torque exerted by each conductor is 1 x 1.5 = 1.5 pound-feet; and the total torque exerted by both conductors is 1.5 + 1.5 = 3 pound-feet.

The armature conductors for a motor are assembled in coils and connected to the commutator riser exactly as in a generator. In the 2-pole motor (fig. 16-6 (A)), the current divides equally in the two paths through the armature. Current flows in one direction in the conductors under the north pole and in the opposite direction in the conductors under the south pole. To develop a continuous motor torque the current in a coil must reverse when the coil passes the dead center position (top and bottom). The function of the commutator is to reverse the current at the proper time to maintain the current flow in the same direction in all conductors under a given pole. The total torque is the sum of the individual torques contributed by all the armature conductors. If there are 200 active conductors each developing a force of 1 pound the total torque will be 200 x 1 x the average moment arm.

The AVERAGE MOMENT ARM is the average of all the perpendicular distances from the armature conductors to the center of rotation. If the field is assumed to consist of uniformly spaced horizontal lines of flux, the average moment arm will be 0.637 of the maximum moment arm, or radius, of the armature.

If the radius of the armature is 1.57 feet, the average moment arm is 0.637 x 1.57 = 1 foot. The total torque exerted by 200 armature conductors developing a force of 1 pound each is 200 x 1 x 1 = 200 pound-feet.

In a 4-pole parallel-wound armature, the current divides into four paths as shown in figure 16-6 (B). The current flows in opposite directions under alternate poles, as in the 2-pole armature, and develops a unidirectional force on all of the armature conductors. The total torque produced by the armature current is equal to the sum of the individual torques developed by each conductor. This torque, T, is proportional to the product of armature current and field strength.

$$T = K_t \Phi I_a, \qquad (16\text{-}1)$$

where K_t is a constant that includes the number of armature conductors, number of paths, and other factors which are constant for a particular machine; Φ the flux per pole and I_a the total armature current. When the speed of a motor is constant, the generated torque due to the armature current is just equal to the retarding torque caused by the combined effect of the friction losses in the motor and the mechanical load. The torque developed by the motor armature is a steady one and does not pulsate as in the case of reciprocating steam engines or internal combustion engines.

HORSEPOWER OF A MOTOR

If the number of revolutions that the armature of a motor makes per minute (or per second), the effective armature radius at which the force acts, and the total force acting at and tangent to this effective radius are known, the horsepower may be determined. Briefly, the horsepower may be determined in the following manner.

Work is accomplished when force acts through distance. For example, when a force of one pound acts through a distance of one foot, one foot-pound of work is accomplished. If 33,000 foot-pounds of work is done in one minute, one horsepower of work is accomplished.

Assume that an armature makes 100 revolutions per minute and that the effective radius is 1.59 feet. The circumference (the distance through which the force moves in one revolution of the armature) is

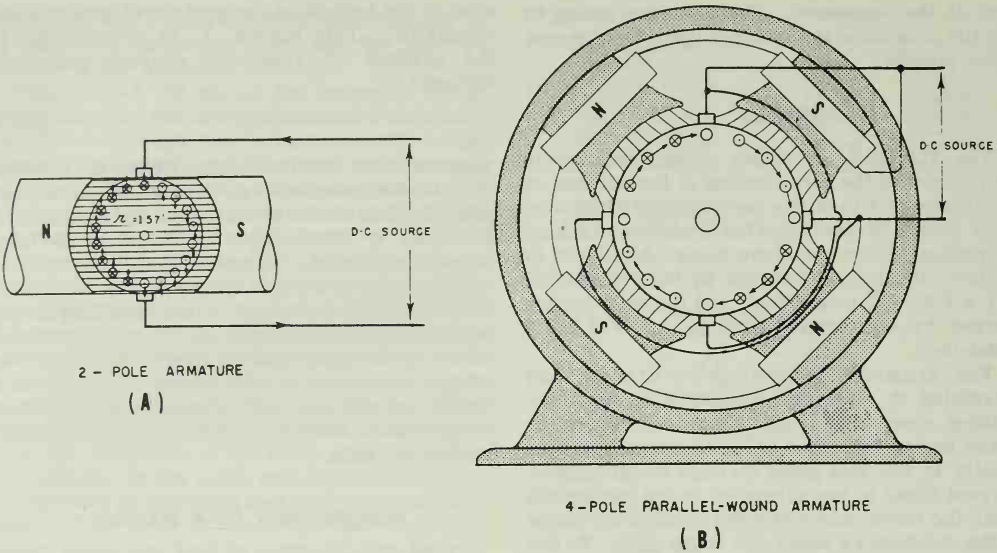
$$\begin{aligned}\text{circumference} &= 2\pi r \\ &= 2 \times 3.14 \times 1.59 = 10 \text{ feet.}\end{aligned}$$

Assuming that a total effective force of 200 pounds acts on the armature tangent to the 10-foot circumference, the work done in one revolution is

$$\text{work} = \text{force} \times \text{distance} = 200 \times 10 = 2{,}000 \text{ foot-pounds.}$$

The work done in 100 revolutions (one minute) is

$$2{,}000 \times 100 = 200{,}000 \text{ foot-pounds.}$$



2 - POLE ARMATURE

(A)

4-POLE PARALLEL-WOUND ARMATURE

(B)

Figure 16-6.—Torque developed in a motor armature.

The horsepower is therefore,

$$\text{h.p.} = \frac{\text{foot-pounds per minute}}{33{,}000} = \frac{200{,}000}{33{,}000} = 6.06 \text{ horsepower.}$$

The horsepower developed by a motor armature may be derived from the general expression,

$$\text{h.p.} = \frac{FV}{33{,}000}, \qquad (16\text{-}2)$$

where F is the total force in pounds tangent to the effective circumference of the armature, and V the velocity of a point on this circumference in feet per minute. Velocity is determined as

$$V = 2\pi r N, \qquad (16\text{-}3)$$

where r is the effective radius of the armature in feet, and N is the armature speed in revolutions per minute. The effective circumference is equal to $2\pi r$.

Substituting equation (16-3) in equation (16-2),

$$\text{h.p.} = \frac{2\pi r N F}{33{,}000} \qquad (16\text{-}4)$$

The torque in pound-feet produced by the motor armature is

$$T = rF. \qquad (16\text{-}5)$$

Substituting equation (16-5) in equation (16-4) and dividing numerator and denominator by 2π,

$$\text{h.p.} = \frac{NT}{5{,}252}. \qquad (16\text{-}6)$$

Substituting the values N = 100 r.p.m. and $T = 1.59 \times 200 = 318$ pound-feet of the preceding example in equation (16-6), the result is

$$\text{h.p.} = \frac{100 \times 318}{5{,}252} = 6.06.$$

Thus, the horsepower developed by a motor depends on its speed and torque. Large, slow-speed motors develop a large torque; whereas other much smaller motors of the same horsepower rating operate at reduced torque and increased speed.

COUNTER E.M.F.

The MOTOR ACTION of a generator was treated in chapter 15: the GENERATOR ACTION of a motor is now considered. By applying the right-hand motor rule to an armature conductor carrying current in the direction indicated in figure 16-7, it will be found that the conductor is forced upward. As the conductor is moved up through the field, it cuts lines of flux and has a voltage induced in it. Applying the left-hand generator rule, it is found that this generated voltage is in opposition to the impressed e.m.f. This counter voltage is induced in the windings of any rotating motor armature and always opposes the impressed voltage. It is called **COUNTER ELECTROMOTIVE FORCE** and is directly proportional to the speed of the armature and the field strength. That is, the counter e.m.f. is increased or decreased if the speed is increased or decreased respectively; the same is true if the field strength is increased or decreased.

The **EFFECTIVE VOLTAGE** (IR drop) in the armature is equal to the impressed voltage minus the counter e.m.f. The armature IR drop varies directly with the current flowing in the armature and the resistance of the armature.

To produce an armature current, I_a, in an armature of resistance, R_a, requires an effective voltage of I_aR_a.

The current flowing through the armature can be found by the equation

$$I_a = \frac{E_a - E_c}{R_a},$$

where I_a is the current flowing through the armature, E_a the impressed (or applied) voltage across the armature, E_c the counter e.m.f., and R_a the armature resistance. This equation can be transposed and written as

$$E_c = E_a - I_aR_a. \qquad (16\text{-}7)$$

In the case of the generator, the generated e.m.f. is equal to the terminal voltage plus the armature resistance drop; and in the case of the motor the generated or counter e.m.f. is equal to the terminal voltage minus the voltage drop in the armature resistance.

Expressing E_a in terms of E_c and I_aR_a,

$$E_a = E_c + I_aR_a.$$

This formula is valid for any d-c motor regardless of speed or load.

The counter e.m.f., E_c, that is induced in a motor armature may be determined by an equation similar to that used to determine the generator voltage in a generator in chapter 15. This equation is

$$E_c = \frac{\Phi ZNP}{10^8 p}, \qquad (16\text{-}8)$$

where Φ is the number of lines of flux per pole, Z the number of face conductors, N the armature speed in revolutions per second, P the number of field poles, and p the number of parallel paths through the armature circuit.

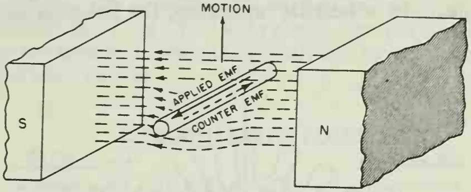


Figure 16-7.—Generator action in a motor.

ARMATURE REACTION

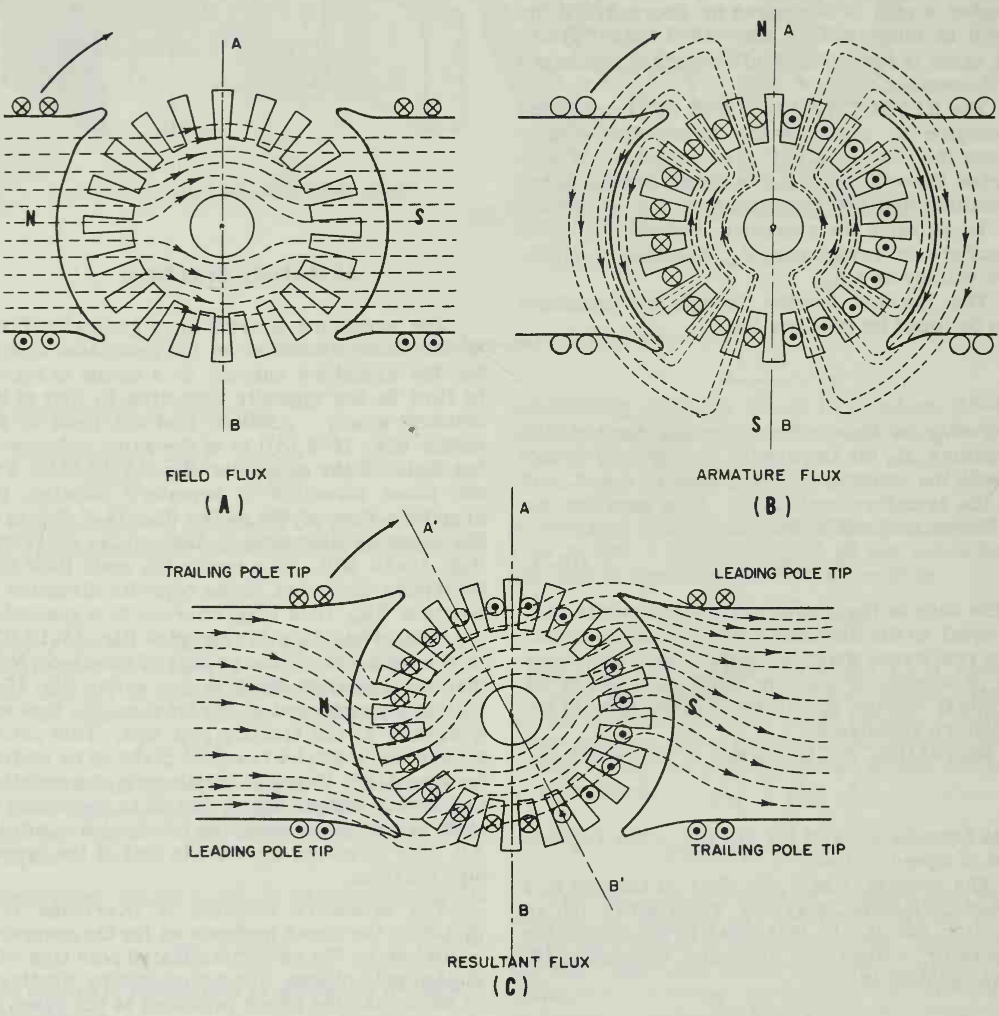
The armature current in a generator flows in the same direction as the generated e.m.f., but the armature current in a motor is forced to flow in the opposite direction to that of the counter e.m.f. Assume that the field of the motor (fig. 16-8 (A)) is of the same polarity as the field of the generator (fig. 15-12 (A)). For the same direction of armature rotation, the armature flux of the motor (fig. 16-8 (B)) is in the opposite direction to that of the generator (fig. 15-12 (B)). In a motor the main field flux is always distorted in the opposite direction to rotation (fig. 16-8 (C)), whereas in a generator the main field flux is distorted (fig. 15-12 (C)) in the same direction as that of rotation. Note that the resultant field in the motor (fig. 16-8 (C)) is strengthened at the leading pole tips and weakened at the trailing pole tips. This action causes the electrical neutral plane to be shifted back to $A'B'$. Thus, to obtain good commutation in a motor without interpoles, it is necessary to shift the brushes from the mechanical neutral, AB, in a direction opposite to that of the armature rotation.

The armature reaction is overcome in a motor by the same methods as for the generator — that is, by the use of laminated pole tips with slotted pole pieces, and compensating windings. In each case the effect produced is the same as that produced in the generator, but it is in the opposite direction.

COMMUTATION

The brush axis, *A'B'* (fig. 16-8 (C)), could be made to coincide exactly with the neutral plane of the combined field. This would eliminate sparking at the brushes if it were not for the self-induced e.m.f. in the commutated coils. Because of the necessity for neutralizing this e.m.f. to eliminate sparking, the brushes must be set slightly behind the neutral plane in a motor. Thus, in both the generator and the motor, the brushes must be moved from the mechanical neutral slightly beyond the electrical neutral plane to neutralize the effect of self-inductance.

The current flowing in the armature coils of a motor (fig. 16-9) must be periodically reversed when the coils are being short-circuited by the



FIELD FLUX
(A)

ARMATURE FLUX
(B)

RESULTANT FLUX
(C)

Figure 16-8.—Armature reaction in a motor.

brushes in order to maintain a unidirectional torque as the coils move under alternate poles. When coil *A* is short circuited by a brush, its current immediately starts to decrease to zero; from zero, the current then builds up to a maximum in the reversed direction by the time the coil moves from position ① to position ②, where the brush no longer short circuits it. As a result of the changing current, a self-induced voltage is set up in the shorted coil, which tends to keep the current from changing. To obtain sparkless commutation it is necessary to overcome this self-induced voltage.

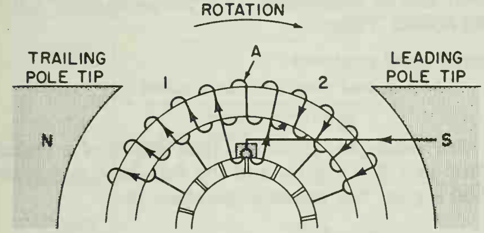


Figure 16-9.—Commutation in a motor.

In any motor the current flows as a result of the applied voltage, and the counter e.m.f. opposes the flow of current. As the current in the commutated coil decreases to zero, the e.m.f. of self-induction tends to keep the current flowing in the same direction, as indicated by the arrow in position ①. Therefore, it aids the applied voltage during this portion of the cycle. As the coil moves into position ② the current increases in the opposite direction, and the self-induced voltage again opposes this current increase. To overcome the self-induced voltage another voltage is introduced into the coil, which opposes the self-induced voltage. The counter e.m.f. is in the proper direction to accomplish this, but the coil being commutated is in the neutral plane and consequently has no counter e.m.f. generated in it.

When the brushes are shifted against the direction of rotation, the coils that are being shorted by the brushes still cut lines of flux from the previous north pole and have a small amount of counter e.m.f. generated in them. Because this counter e.m.f. opposes the applied voltage it also opposes the self-induced voltage, thus resulting in rapid reversal of coil current and in sparkless commutation.

When the load on the motor increases, armature reaction increases and the electrical neutral plane is shifted further in the direction opposite to that of the armature rotation. To maintain sparkless commutation, the plane of the brushes will have to be shifted slightly beyond the electrical neutral plane. When the load is reduced, the brushes are shifted in the opposite direction. Thus, for sparkless commutation, it is necessary to manually shift the brushes when the load varies.

COMMUTATING POLES

Commutating poles are as important in motors as in generators. Nearly all motors of more than one horsepower depend on COMMUTATING POLES, sometimes called INTERPOLES, rather than on the shifting of the brushes to obtain sparkless commutation. Essentially the only difference between the interpole generator and the interpole motor is that in the generator the interpole has the same polarity as the main pole AHEAD of it in the direction of rotation, but in the motor the interpole has the same polarity as the main pole BACK of it.

Without interpoles the e.m.f. of self-induction is overcome by commutating the coil while it is cutting the flux of the main pole it is just leaving. Therefore, if the interpole is to overcome the e.m.f. of self-induction, it must have the same polarity as the main pole it is leaving. This is a north pole in the example of figure 16-9.

The interpole series field coil in a motor is connected to carry the armature current, as in the generator. As the load varies, the interpole flux varies, and commutation is automatic with load change. It is not necessary to shift the brushes when there is an increase or decrease in load. The brushes are located on the no-load neutral and remain in that position for all conditions of load.

The motor may be reversed by reversing the direction of the current in the armature. When the armature current is reversed, the current through the interpole is also reversed, and therefore the interpole still has the proper polarity to provide automatic commutation.

The direction of the counter e.m.f. in the interpole motor with clockwise rotation (fig. 16-10) illustrates that coils under the interpoles do not contribute to the armature counter voltage, but that only those coils under the main

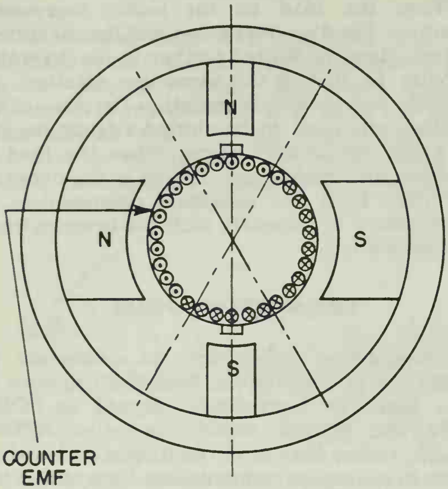


Figure 16-10.—Effect of interpoles on armature counter e.m.f.

poles contribute to it. The total counter voltage generated in the conductors on each half of the armature is equal to the algebraic sum of the voltages generated in each conductor between the upper and lower brush. Because those under the upper north interpole generate an equal and opposite voltage to those under the lower south interpole, the remaining conductors under the main field poles generate the armature counter e.m.f. that controls the armature load current and the speed-torque characteristics of the motor. It is important that the brushes be set in the correct neutral plane, otherwise the commutation will be impaired and the motor characteristics will be altered.

SPEED REGULATION

SPEED REGULATION is the ability of a motor to maintain its speed when a load is applied. It is an inherent characteristic of a motor and remains the same as long as the applied voltage does not vary — that is, unless a physical, or mechanical, change is made in the machine. The speed regulation of a motor is a comparison of its no-load speed to its full-load speed and is expressed as a percentage of full-load speed. Thus,

$$\text{percent speed regulation} = \frac{\text{no-load speed} - \text{full-load speed}}{\text{full-load speed}} \times 100.$$

For example, if the no-load speed of a shunt motor is 1,600 r.p.m. and the full-load speed is 1,500 r.p.m. the speed regulation is

$$\frac{1{,}600 - 1{,}500}{1{,}500} \times 100 = 6.6 \text{ percent.}$$

The LOWER the speed-regulation percentage figure of a motor, the more constant the speed will be under varying load conditions and the BETTER will be the speed regulation. The HIGHER the speed-regulation percentage figure, the POORER is the speed regulation.

SPEED CONTROL refers to the external means of varying the speed of a motor under any load.

Shunt Motors

SPEED REGULATION OF A SHUNT MOTORS

The field circuit of a shunt motor is connected across the line and is thus in parallel with the armature the same as it is in the shunt generator (fig. 15-16 (B)). If the supply voltage is constant, the current through the field coils, and consequently the field flux, will be constant.

When there is no load on the shunt motor, the only torque necessary is that required to overcome bearing friction and windage. The rotation of the armature coils through the field flux establishes a counter e.m.f. that limits the armature current to the relatively small value required to establish the necessary torque to run the motor on no load.

When an external load is applied to the shunt motor it tends to slow down slightly. The slight decrease in speed causes a corresponding decrease in counter e.m.f. If the armature resistance is low, the resulting increase in armature current and torque will be relatively large. Therefore, the torque is increased until it matches the resisting torque of the load. The speed of the motor will then remain constant at the new value as long as the load is constant.

Conversely, if the load on the shunt motor is reduced, the motor tends to speed up slightly. The increased speed causes a corresponding increase in counter e.m.f. and a relatively large decrease in armature current and torque.

Thus, it may be seen that the amount of current flowing through the armature of a shunt motor depends on the load on the motor. The larger the load, the larger the current; and conversely, the smaller the load, the smaller the current. The change in speed causes a change in counter e.m.f. and armature current in each case.

Figure 16-11 indicates graphically what happens when the load is applied or removed from a shunt motor. In this figure it is assumed that the field strength remains constant.

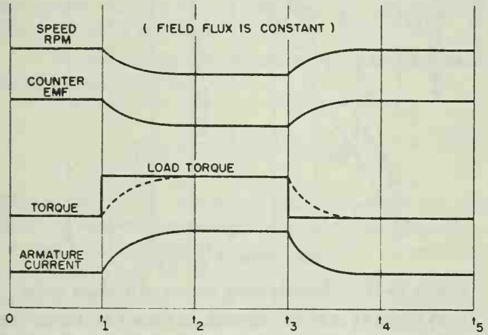


Figure 16-11.—Shunt motor load-speed-torque-e.m.f. relationships with respect to time.

During the interval between 0 and t_1 the motor operates under conditions of equilibrium — that is, the speed, counter e.m.f., torque, and armature current have steady values. At t_1 a load is applied to the motor. Instantly, the load-torque curve rises, but the inertia of the armature prevents the generated torque from rising instantly with it. Because the load torque exceeds the generated torque in the motor armature, the motor speed is reduced until a balance is again obtained. When the generated torque is again equal to the load torque deceleration ceases and the motor operates at a constant reduced speed.

At time t_2 this state of equilibrium, corresponding to the new load, is reached. At time t_3 the load is suddenly removed. The load torque drops instantly, but the armature inertia prevents the generated torque from falling instantly with it. Likewise, the armature inertia prevents the armature speed from increasing suddenly. Because the generated torque exceeds the load torque, the motor accelerates. As the speed increases, the counter e.m.f. increases proportionately. This opposes the applied e.m.f., and the armature current is reduced until the generated torque and load torque are again in a state of equilibrium. The speed then levels off to a constant value.

The operational features of a shunt motor are indicated in table 16-1. The variation of line current, armature current, counter e.m.f., speed, torque, and efficiency, with varying load conditions are indicated. The values are based on a 1-horsepower 100-volt shunt motor having a field current of 1 ampere and an armature resistance of 1 ohm.

When the armature current is 1 ampere the armature *IR* drop is 1 volt, and the counter e.m.f. is the difference between the applied voltage and the *IR* drop, or 100 - 1 = 99 volts. The speed at this load is assumed to be 990 r.p.m. At this load the motor torque is assumed to be 0.7 pound-foot. The output power, P_o, in watts is

$$P_o = \frac{NT}{5,252} \times 746 = 0.142\,NT = 0.142 \times 990 \times 0.7 = 98.4 \text{ watts.}$$

Table 16-1.—Operational features of a shunt motor.

I Line (amperes)	I Arma-ture (amperes)	Counter e.m.f. (volts)	Speed (r.p.m.)	Torque (lb-ft)	Output 0.142NT (watts)	Input (watts)	Efficiency (percent)	Load
[1]2	[1]1	[1]99	[1]990	[1]0.7	98.4	200	49.2	Light.
4	3	97	970	2.1	289	400	72.2	Do.
6	5	95	950	3.5	472	600	78.5	Do.
8	7	93	930	4.9	646	800	80.8	Do.
10	9	91	910	6.3	815	1,000	81.5	Normal.
21	20	80	800	14	1,590	2,100	76	Over.

---

[1] Assumed.

The constant 746 is used to convert horsepower output into an equivalent number of watts output (1 horsepower = 746 watts).

The total input current to the motor is equal to the sum of the field current and the armature current, or 1 + 1 = 2 amperes. The input power is the product of the applied voltage and the total input current, or 100 x 2 = 200 watts. The efficiency is

$$\frac{\text{output}}{\text{input}} \times 100 = \frac{98.4}{200} = 49.2 \text{ percent at this load.}$$

The torque calculations for other values of load are based on the proportionality between armature current and torque. For example, if the torque is 0.7 pound-foot when the armature current is 1 ampere, the torque for an armature current of 2 amperes will be 2 x 0.7 = 1.4 pound-feet.

The speed calculations are based on the proportionality between speed and counter voltage. For example, when the armature current is 2 amperes the armature *IR* drop is 2 x 1 = 2 volts, and the counter e.m.f. is 100 - 2 = 98 volts. If the speed is 990 r.p.m. when the counter e.m.f. is 99 volts, the speed at 98 volts counter e.m.f. will be 980 r.p.m.

The characteristic curves of a 5-horsepower 230-volt shunt motor are shown in figure 16-12. These curves include speed, torque, efficiency, and input current. The speed curve is almost a horizontal line, and the regulation is good. The torque varies directly with the output load and armature current because the field is approximately constant over the load range.

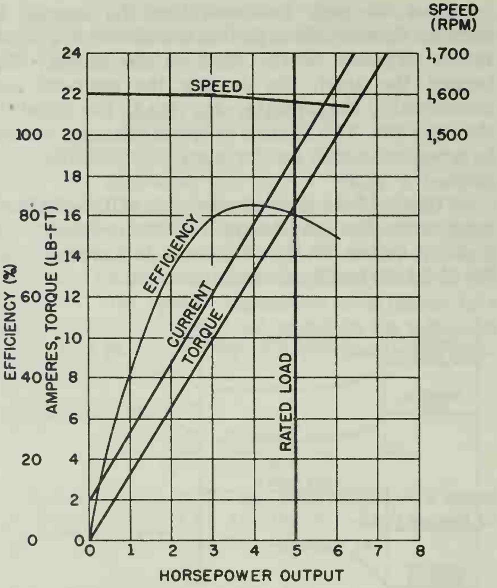


Figure 16-12.—Characteristic curves of a shunt motor.

The speed regulation of a shunt motor is generally better than the voltage regulation of the same machine when operating as a shunt generator. This action is due to the fact that armature reaction in a generator weakens the field and lowers the terminal voltage, whereas armature reaction in a motor weakens the field and tends to increase the motor speed. Armature resistance is low, and a decrease in field strength and counter e.m.f. (for example, of 5 percent) might result in an increase in armature current and accelerating force on the armature conductors of 50 percent with resulting increase in armature speed. In general, however, armature reaction in a motor weakens the field only slightly and does not cause the speed to increase with load, but to decrease less than it would if the armature reaction were not present.

USES OF SHUNT MOTORS

From the preceding considerations it is evident that a shunt motor is essentially a constant-speed machine. Although the speed may be varied by varying the current through the field winding (for example, by means of a field rheostat), the speed remains nearly constant for a given field current.

The constant-speed characteristic makes the use of shunt motors desirable for driving machine tools or any other device that requires a constant-speed driving source.

Where there is a wide variation in load, or where the motor must start under a heavy load, series motors have desirable features not found in shunt motors.

Series Motors

SPEED REGULATION OF SERIES MOTORS

The field coils of a series motor are connected in series with the armature like those of the series generator in figure 15-16 (B). With relatively low flux density in the field iron, the series field strength is proportional to armature current I_a. The torque developed by the motor armature is proportional to $I_a\Phi$; and because Φ is also proportional to I_a, the torque is proportional to I_a^2.

If the supply voltage is constant, the armature current and the field flux will be constant only if the load is constant. If there were no load (this is never done) on the motor, the armature would speed up to such an extent that the windings might be thrown from the slots and the commutator destroyed by the excessive centrifugal forces. The reason why the speed becomes excessive on no load is explained in the following manner.

The speed of a series motor may be expressed mathematically as

$$\text{r.p.m.} = \frac{K\,[E - I_a(R_a + R_s)]}{\Phi}; \qquad (16\text{-}9)$$

Where K is a constant that depends on such factors as the number of poles, the number of current paths, and the total number of armature conductors; E is the voltage applied across the entire motor; I_a is the armature current; R_a is the armature resistance; R_s is the resistance of the series field; and Φ is the field strength. The factor $E - I_a\,(R_a + R_s)$ represents mathematically the counter e.m.f., E_c. The applied voltage must then be equal to the counter voltage plus the voltage drop in the armature, or

$$E = E_c + I_a(R_a + R_s). \qquad (16\text{-}10)$$

The armature always tends to rotate at such a speed that the sum of the counter voltage, E_c, and the I_aR_a drop in the armature will equal the applied voltage, E. If the load is removed from the motor, the armature will speed up and a higher counter e.m.f. will be induced in the armature. This reduces the current through the armature and the field. The weakened field causes the armature to turn faster. The counter e.m.f. is thus increased, and the speed is further increased until the machine is destroyed. For this reason, series motors are never belt-connected to their loads. The belt might come off and the motor would then overspeed and destroy itself. Series motors are always connected to their loads directly, or through gears.

As the load increases, the armature slows down and the counter e.m.f. is reduced. The current through the armature is increased and likewise the field strength is increased. This reduces the speed to a very low value. The armature current, however, is not excessive because the torque developed depends on BOTH the field flux and the armature current.

The operational features of a series motor are indicated in table 16-2. The variation of line current, counter e.m.f., speed and torque under varying load conditions are indicated. The values are based on a 0.5-horsepower 100-volt series motor having a field resistance of 1 ohm and an armature resistance of 1 ohm.

When the armature current is 5 amperes, the armature and field IR drop is 10 volts, and the counter e.m.f. is the difference between the applied voltage and the IR drop, or 100 - 10 = 90 volts. At this load the speed is assumed to be 900 r.p.m. and the motor torque is assumed to be 3 pound-feet. The output power, P_o, in watts is

$$P_o = 0.142NT = 0.142 \times 900 \times 3 = 383.4 \text{ watts.}$$

The input power is the product of the applied voltage and the current through the field and the armature, or 100 x 5 = 500 watts. The efficiency

Table 16-2.—Operational features of a series motor.

I Armature (amperes)	Counter e.m.f. (volts)	Speed (r.p.m.)	Torque (lb-ft)	Output 0.142 NT (watts)	Input (watts)	Efficiency (percent)
[1]5	[1]90	[1]900	[1]3	383.4	500	76
10	80	400	12	681.6	1,000	68
15	70	233	27	893.3	1,500	59
20	60	150	48	1,022.4	2,000	51
25	50	100	75	1,065.0	2,500	42

[1] Assumed.

(the output divided by the input) is $\frac{383.4}{500}$, or 76.8 percent.

The speed calculations are based on the following considerations. As has been explained (see equation 16-8), the counter e.m.f., E_c is determined as

$$E_c = \frac{\Phi ZNP}{10^8 p}.$$

It is also determined as

$$E_c = E - I_a(R_a + R_f).$$

These equations may be equated as

$$\frac{\Phi ZNP}{10^8 p} = E - I_a(R_a + R_f).$$

Assume that when 5 amperes flow through the field coil (and the armature) $\Phi = 10^6$ lines of force. Assume also that Z = 600 conductors. There are 2 poles (P = 2) and 2 paths (p = 2) through the armature. If N is divided by 60, the number of revolutions will be determined for an interval of 1 minute. Thus,

$$\frac{10^6 \times 600 \times N \times 2}{10^8 \times 60 \times 2} = 100 - 5(1 + 1),$$

and,

$$N = 900 \text{ r.p.m.}$$

If the current is increased to 10 amperes (doubled), the flux is also assumed to double. Thus,

$$\frac{2 \times 10^6 \times 600 \times N}{10^8 \times 60} = 100 - 10(1 + 1).$$

The number of revolutions per minute becomes

$$N = 400 \text{ r.p.m.}$$

The torque varies as the square of the current. Thus, when the current is doubled, the torque is increased four times.

The characteristic curves of a series motor are shown in figure 16-13. As in the case of the shunt motor, these curves include speed, torque, efficiency, and input current. As stated previously, the torque varies as the square of the armature current (below saturation) and the speed decreases rapidly as the load is increased.

USES OF SERIES MOTORS

As indicated in figure 16-13, the torque increases with load. When the load on a series motor is increased, the speed and the counter e.m.f. decrease and the armature current and field strength increase. There is therefore an increase in torque with decrease in speed with the result that the increased load on the motor is limited by the decrease in speed.

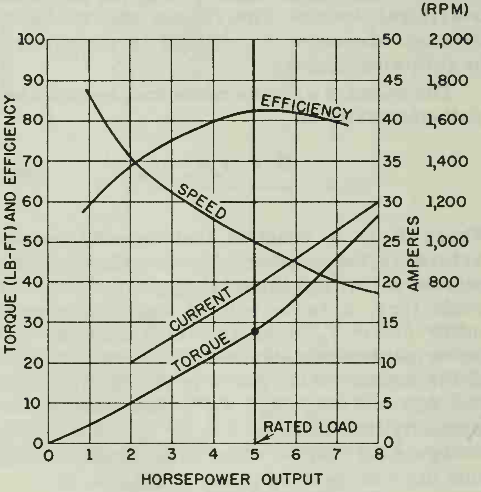


Figure 16-13.—Characteristic curves of a series motor.

When a heavy load is suddenly thrown on a shunt motor, it attempts to take on the load at only slightly reduced speed and counter emf. The flux remains essentially constant and therefore the increased torque is proportional to the increase in armature current. With heavy overload the armature current becomes excessive and the temperature increases to a very high value. The shunt motor cannot slow down appreciably on heavy load, as can the series motor; hence the shunt motor is more susceptible to overload.

For example, assume that a d-c motor is used to move an electric truck up an incline. If it is a shunt motor it will attempt to maintain almost the same speed up the incline as on the level and consequently excessive current may be drawn through the armature, since the field flux remains almost constant. If it is a series motor, the speed must decrease more than the flux increases in order to have a reduction in counter e.m.f. and an increase in armature current $\left(E_c = \frac{\Phi ZNP}{10^8 p}\right)$. The decrease in speed protects the series motor from excessive overload, and the armature current is limited by the counter voltage and the combined resistance of the armature and series field.

The series motor is therefore used where there is a wide variation in both torque and speed such as in traction equipment, blower equipment, hoists, cranes, and so forth.

Compound Motors

Compound motors, like compound generators, have both a shunt and a series field. In most cases the series winding is connected so that its field aids that of the shunt winding, as shown in figure 16-14 (A). Motors of this type are called CUMULATIVE COMPOUND motors. If the series winding is connected so that its field opposes that of the shunt winding, as shown in figure 16-14 (B), the motor is called a DIFFERENTIAL COMPOUND motor. Under full load, the ampere-turns of the shunt coil are greater than the ampere-turns of the series coil.

In the CUMULATIVE COMPOUND motor the speed decreases (when a load is added) more rapidly than it does in a SHUNT motor, but less rapidly than in a series motor. Series field strength increases as in a series motor. Transposing equation (16-10) for armature current,

$$I_a = \frac{E - E_c}{R_a + R_s}.$$

To increase I_a, E_c must decrease. As in the series motor, the decrease in speed is necessary to allow the counter e.m.f. to decrease at the same time the field increases. Because the torque varies directly as the product of the armature current and the field flux (equation 16-1), it is evident that the cumulative compound motor has greater starting torque than does the shunt motor for equal values of armature current and shunt field strength. The performance of this type of motor approaches that of a shunt motor as the ratio of the ampere-turns of the shunt winding to the ampere-turns of the series winding becomes greater. The performance approaches that of a series motor as this ratio becomes smaller.

If the load is removed from this type of motor it tends to speed up, and the counter e.m.f. increases. The current in the series field is reduced, and the greater portion of the field flux is produced by the shunt field coils. The compound motor then has characteristics similar to a shunt motor; and unlike the series motor, there is a definite no-load speed.

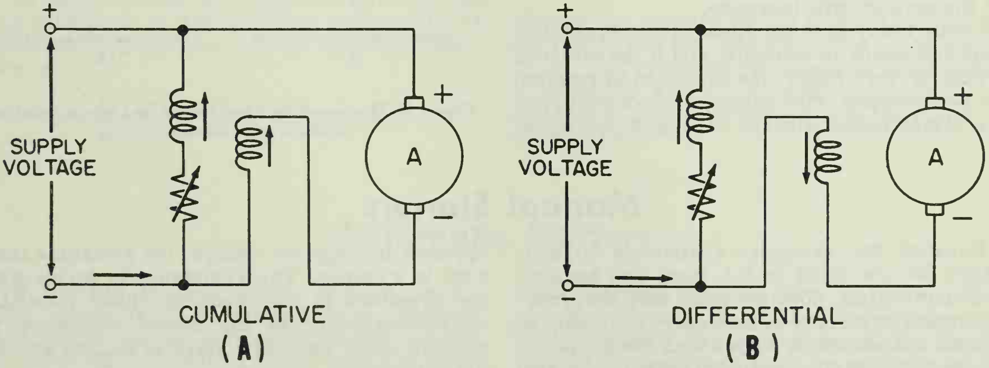


Figure 16-14.—Types of compound motors.

Because the total flux increases when there is an increase in load, there is a greater proportional increase in torque than in armature current. Therefore, for a given torque increase, this type of motor requires less increase in armature current than the shunt motor, but more than the series motor.

In some operations it is desirable to use the cumulative series winding to obtain good starting torque; and when the motor comes up to speed, the series winding is shorted out. The motor then has the improved speed regulation of a shunt motor.

In a differential compound motor, because of the opposition of the series field to the shunt field, the flux decreases as the load and armature current increase. From equation (16-9), it is seen that a decrease in flux causes an increase in speed. However, because the speed is proportional to $\frac{E_c}{\Phi}$, if both factors vary in the same proportion, the speed will remain constant. This action may occur in the differential compound motor. If more turns are added to the series coil, it is possible to cause the motor to run faster as the load is increased.

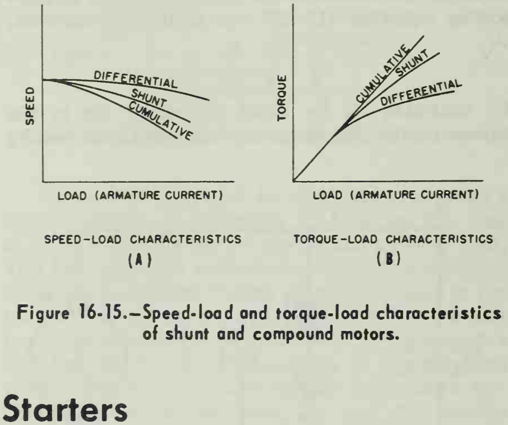
More armature current is required of the differential compound motor than of the shunt motor for the same increase in torque. This results from the fact that an increase in armature and series-field current reduces the field flux. Since the torque acting on the armature is proportional to the product of armature current and field strength, a decrease in field strength must be accompanied by a disproportionate increase in armature current in order that the product will increase.

Under heavy load the speed of the differential compound motor is unstable; and if the overload current is very heavy, the direction of rotation may be reversed. Thereafter, the motor will run as a series motor with the danger of overspeed on no load that is the inherent characteristic of all series motors.

The characteristics of the differential compound motor are somewhat similar to those of the shunt motor, only exaggerated in scope. Thus, the starting torque is very low, and the speed regulation is very good if the load is not excessive. However, because of some of the undesirable features, this type of motor does not have wide use.

Figure 16-15 (A) shows the relative speed-load characteristics of shunt motors, cumulative compound motors, and differential compound motors. Although the speed of each of the motors is reduced when the current through the armature is increased (load is increased), the cumulative motor has the greatest decrease in speed. Likewise, in figure 16-15 (B) the cumulative motor has the greatest increase in torque with increase in load.

Cumulative compound motors are used under conditions where large starting torque is necessary, where a relatively large change in speed can be tolerated, and where the load may be removed from the motor with safety. These motors are therefore used for hoists, punches, shears, and so forth.



SPEED-LOAD CHARACTERISTICS
(A)

TORQUE-LOAD CHARACTERISTICS
(B)

Figure 16-15.—Speed-load and torque-load characteristics of shunt and compound motors.

Manual Starters

Because the armature resistance of many motors is low (0.05 to 0.5 ohm) and because the counter e.m.f. does not exist until the armature begins to turn, it is necessary to employ an external resistance in series with the armature to keep the initial armature current to a safe value. As the armature begins to turn, the counter e.m.f. increases. Because the counter e.m.f. opposes the applied voltage, the armature current is reduced. The resistance in series with the armature is then reduced either manually or automatically as the motor comes up to normal speed and full voltage is applied across the armature.

The relation between armature current, I_a, applied voltage E_a, counter e.m.f., E_c, armature resistance, R_a, and starting resistance, R_s, for a shunt motor is

$$I_a = \frac{E_a - E_c}{R_a + R_s}.$$

Assume that for the shunt motor shown in figure 16-16, $E_a = 100$ volts, $R_a = 0.1$ ohm, $R_s = 0.9$ ohm, and the normal full-load armature current is 10 amperes. Without the starting resistance, the armature current would be

$$I_a = \frac{E_a}{R_a} = \frac{100}{0.1} = 1{,}000 \text{ amperes.}$$

This is 100 times the normal current for the motor and would obviously burn up the armature insulation and cause excessive acceleration forces.

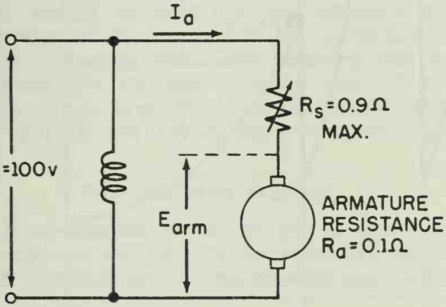


Figure 16-16.—Shunt motor with manual starting resistance.

In order to limit the initial surge of current to a maximum of 100 amperes (arbitrarily, 10 times the full-load current), the starting resistance is

$$R_s = \frac{E_a - I_a R_a}{I_a} = \frac{100 - 100 \times 0.1}{100} = 0.9 \text{ ohm.}$$

The relation of E_a; I_a; the starting resistance, R_s; motor speed, and counter e.m.f. during the accelerating period is shown in the curves of figure 16-17 and in table 16-3.

Initially, the full starting resistance of 0.9 ohm is inserted in series with the armature resistance of 0.1. The speed and counter e.m.f. are zero, and the armature current is limited to 100 amperes by the armature resistance of 0.1 ohm, acting in series with the starting resistance of 0.9 ohm. As the speed and counter e.m.f. increase, the counter e.m.f. subtracts a greater magnitude of voltage from the applied e.m.f., and the armature current is reduced from 100 amperes to some lower value. When the speed is 500 r.p.m. the counter e.m.f. is 50 volts and the current is

$$I_a = \frac{100 - 50}{0.1 + 0.9} = 50 \text{ amperes.}$$

Suppose that at the instant t_1, when the motor speed is 500 r.p.m., the starting switch is moved to the 0.4-ohm tap. The counter e.m.f. of 50 volts subtracts from the 100 volts applied, leaving 50 volts to cause the armature current to again increase to $\frac{100 - 50}{0.4 + 0.1} = 100$ amperes at time t_1. The armature speed and counter e.m.f. cannot increase suddenly, but rise gradually during the interval from t_1 to t_2. Therefore, the armature current is decreased gradually, and at t_2, when the counter e.m.f. is 75 volts and the speed is 750 r.p.m., the current is

$$I_a = \frac{100 - 75}{0.4 + 0.1} = 50 \text{ amperes.}$$

Moving the starting switch to the 0.15-ohm tap, the 0.025-ohm tap, and the 0-ohm tap at instants t_2, t_3, and t_4 causes the motor to accelerate to a speed of 970 r.p.m. with variations in the armature current as indicated in the figure and in the table.

Automatic Starters

If a motor is at a remote location, or if a large motor is to be started, it is generally desirable to use an automatic starter to bring the motor up to operating speed. Although small motors are started by means of manually operated starters, difficulties are encountered when starting large motors. In the manually-operated starter, the skill with which the operator regulates the magnitude of the starting current is dependent upon his experience. Too much time may be taken by an overcautious operator or the maximum permissible current

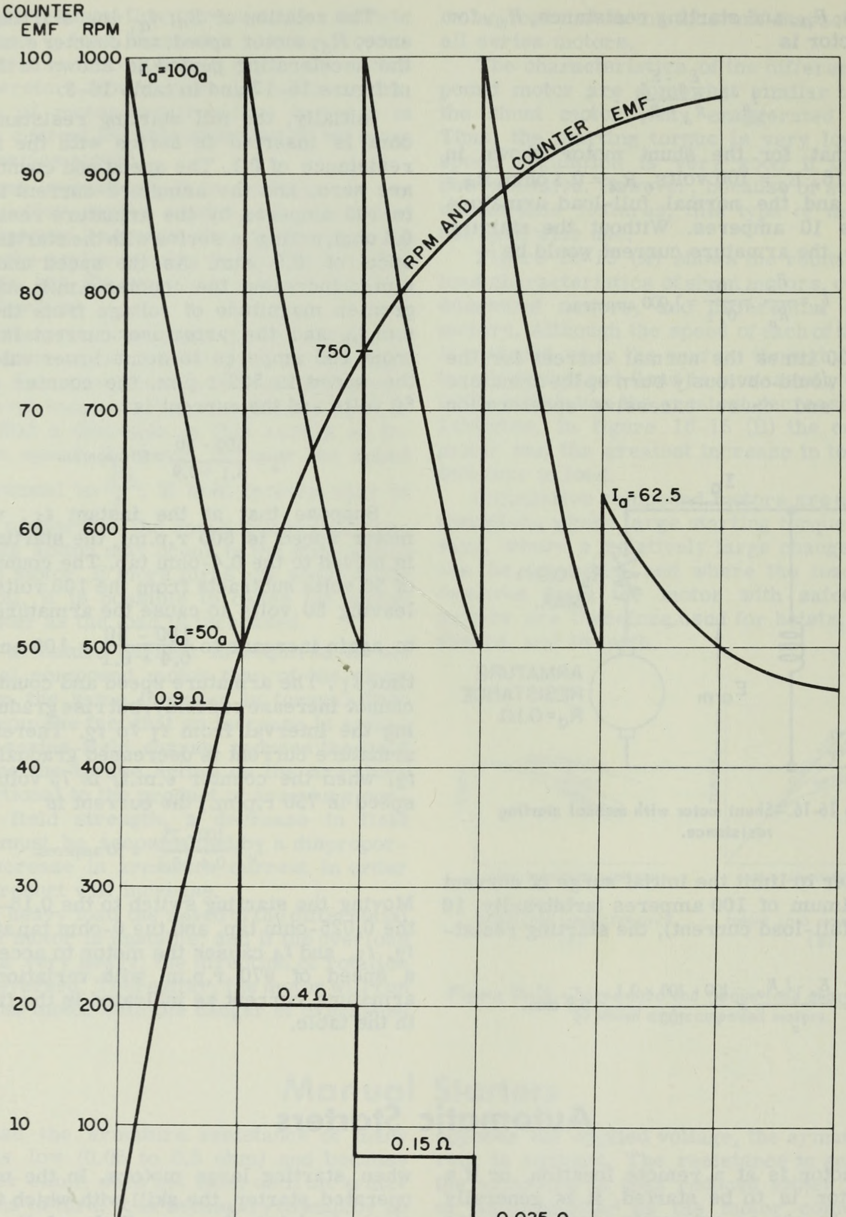


Figure 16-17.—Shunt motor starting curves.

Table 16-3.—Starting characteristics of a shunt motor.

Armature current (amperes)	Starting resistance (ohms)	Armature volts ($E_a - I_aR_s$)	Speed (r.p.m.)	Counter e.m.f. volts $[E_a - I_a(R_a + R_s)]$
100	0.9	10	0	0
50	0.9	55	500	50
100	0.4	60	500	50
50	0.4	80	750	75
100	0.15	85	750	75
50	0.15	92.5	875	87.5
100	0.025	97.5	875	87.5
50	0.025	98.75	937.5	93.75
62.5	0	100	937.5	93.75
30	0	100	970	97

for the motor may be exceeded by a careless one. In order that time shall not be wasted and the motor receive maximum safe current during the acceleration period, an automatic device should be used that will interpret the conditions of the load and act accordingly.

The following automatic starters will be discussed: (1) The time-element type, (2) the counter e.m.f. type, (3) the shunt current-limit type, and (4) the series current limit type.

TIME-ELEMENT STARTER

A time-element starter is one in which the resistance in series with the armature is reduced a certain amount during each succeeding unit of time regardless of the load on the motor. One type of time-element starter is shown in figure 16-18. Initially, the full value of the starting resistance is inserted in series with the armature, and its current is therefore limited to a safe value. When the switch is closed, the full-line voltage is impressed across the accelerating solenoid and across the shunt field. The solenoid immediately begins to draw the iron core upwards, and the starting resistance is gradually cut out of the armature circuit. The speed with which the resistance is cut out depends on the size of the orifice (the hole through which the oil flows) in the dashpot. The smaller the orifice, the greater the time delay. The time delay should be such that as

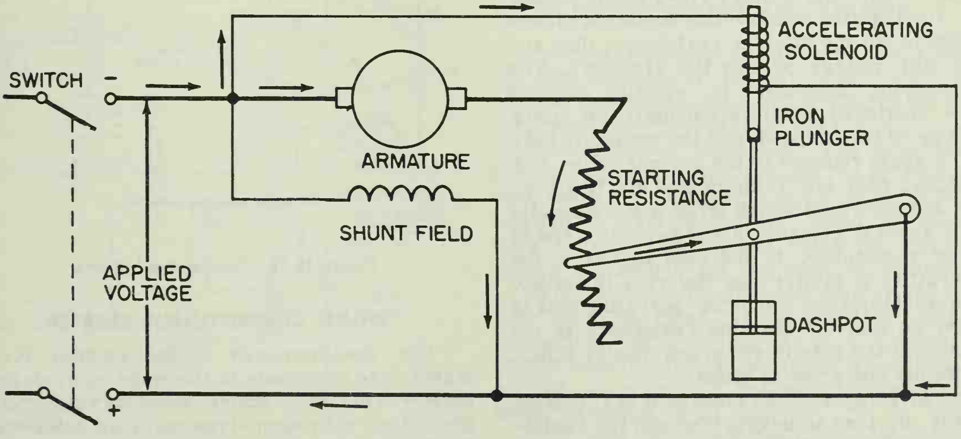


Figure 16-18.—Time-element starter.

the speed and the counter e.m.f. builds up, the starting current is maintained at the maximum safe value during the accelerating period. During the time required to reach full speed, the resistance is completely removed from the circuit.

The advantages of the time-element type of automatic starter are that its cost is low, the wiring is simple, and starting is generally sure. The disadvantages are that the amount of load cannot be sensed — that is, the resistance is removed at the same rate whether the load is heavy or light, the motor is not protected on overload, and the dashpot is a source of trouble.

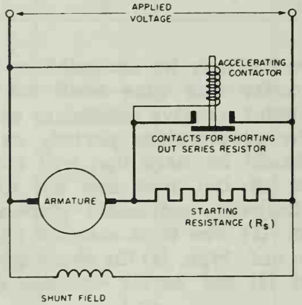
COUNTER E.M.F. STARTER

The counter e.m.f. starter depends for its operation on the counter e.m.f. developed across the armature. As may be seen from figure 16-19 (A), the solenoid that activates the contacts is connected directly across the armature. It therefore responds to armature voltage, which is only slightly higher than the counter e.m.f.

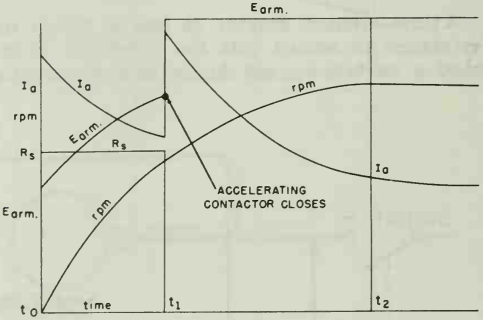
At start (fig. 16-19 (B)), time t_0, the armature current flowing through the starting resistance causes a reduced voltage to be applied to the armature and the accelerating contactor will not immediately close its contacts due to low voltage across its operating coil. As the motor accelerates, the rising counter e.m.f. causes the armature current and voltage drop across the starting resistance to reduce. At the same time, the voltage across the armature increases. When this voltage rises to the proper value, time t_1, the accelerating contactor closes and shorts out the starting resistance, thus applying full voltage across the armature. The accompanying increase in starting current causes continued acceleration until the motor comes up to rated speed, and the armature current is again reduced to the normal value. For simplicity, only one resistor and starting contactor are shown, although large motors usually employ several contactors and several steps of starting resistance. If the load is heavy, the acceleration is slower and the rise in voltage on the accelerating contactor operating coil is delayed so that the starting resistance is not cut out until the rise in speed and counter e.m.f. permits the contactor to close.

The advantages of the counter e.m.f. starter are that the load is interpreted and the resistance cut out accordingly, the cost is low, the wiring is simple, and the dashpot is not used.

The disadvantages of the counter e.m.f. starter are that if the line voltage varies, the acceleration may become erratic. For example, if the line voltage rises, the starting resistance may be removed too soon; and if it falls, the starting contactor may not be activated at all. The starting contactor coils are designed to close the contactor on one value of voltage and to operate continuously on an increased voltage. Thus, they are sensitive to voltage change and will not operate properly if line voltage fluctuations occur.


APPLIED VOLTAGE
ACCELERATING CONTACTOR
CONTACTS FOR SHORTING OUT SERIES RESISTOR
ARMATURE
STARTING RESISTANCE (R_s)
SHUNT FIELD

CIRCUIT
(A)



ACCELERATION CURVES
(B)

Figure 16-19.—Counter e.m.f. starter.

SHUNT CURRENT-LIMIT STARTER

The disadvantages of the counter e.m.f. starter are overcome in the shunt current-limit starter. This motor starter employs accelerating contactors with shunt-type operating coils wound for full-line voltage. Each contactor includes an interlocking series relay, the operation of which is limited by the motor starting current. When the series relay closes its contacts, the shunt operating coil of the accelerating contactor is energized and a section of starting resistance is cut out of the armature circuit. This type of motor starter thus derives its name from the fact that the accelerating contactors are shunt operated and the closure of the series relays is limited by the magnitude of the armature current.

Figure 16-20 is a simplified schematic diagram of a shunt current-limit starter operating in connection with a pushbutton starter with no-voltage release holding-contacts. When the ON button is pressed down momentarily, the no-voltage release coil is energized. The holding relay contacts and the line contacts are closed. The series relay is mechanically released, and its contacts would close were it not for the fact that the armature current flows through the series coil and holds its core up, thus keeping its contacts open. Thus, it may be seen that current flows from the negative terminal of the voltage source through the armature, through the starting resistor, through the series relay coil, and back to the positive terminal of the voltage source.

As the motor speeds up, the counter e.m.f. increases, and the armature current is reduced accordingly. The field of the series relay is thereby weakened and the relay contacts are closed. This action energizes the coil of the accelerating contactor and its contacts close, thus shorting out the starting resistor and the series relay. The full-line voltage is then safely applied across the armature. The series relay and accelerating contactor contacts remain closed until the line contacts are opened.

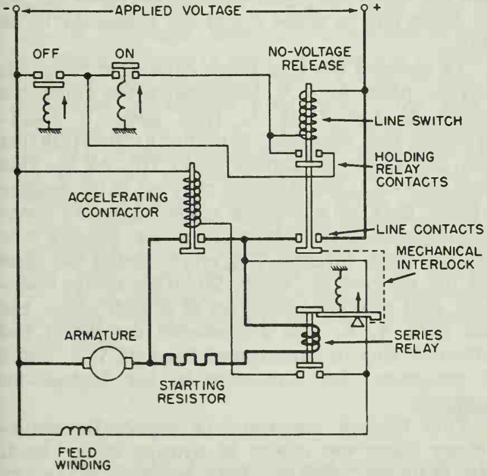


Figure 16-20.—Shunt current-limit starter.

When the OFF button is pressed, current through the no-voltage release coil is interrupted and the holding relay contacts, the line contacts, and the series relay contacts are opened. Line voltage is thus removed from the motor.

Although for simplicity only one starting resistor is shown in a practical system, two or three are commonly used. Additional accelerating contactors and interlocking series relays are then used to remove the starting resistance in steps as the motor comes up to speed.

The advantage of the shunt current-limit starter is that starting resistance is cut out of the armature circuit only after the speed has built up and the motor current has been reduced to a safe value irrespective of line voltage fluctuations. If the load is too great for the motor to accelerate normally, the counter e.m.f. cannot build up sufficiently to reduce the current through the series relay to cause its contacts to fall closed. Therefore, the starting resistance remains in the circuit and the armature is protected against excessive current.

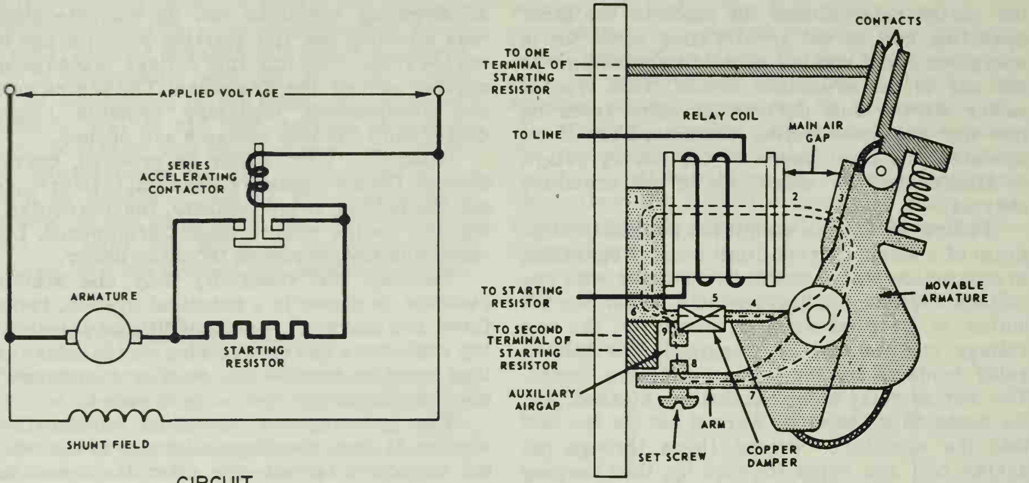
The disadvantage is that the accelerating units are complicated and expensive.

SERIES CURRENT-LIMIT STARTER

The series current-limit type of motor starter was designed to accelerate motors and to provide the same protection afforded by the shunt current-limit type of starter, but to do the job with less complicated equipment. The interlocking series relays are omitted and the accelerating contactors are designed to lock open on the initial in-rush of starting current. When the current falls to a predetermined value the contactor closes and shorts out the starting resistance.

In the series current-limit starter, the relay coil which operates the accelerating contactor is series wound — that is, it is connected in series with the armature circuit. The simplified circuit, showing only one starting resistor, is shown in figure 16-21 (A).

One type of magnetically operated switch that makes this type of starter possible is shown in figure 16-21 (B). The initial current


APPLIED VOLTAGE
SERIES ACCELERATING CONTACTOR
ARMATURE
STARTING RESISTOR
SHUNT FIELD
CONTACTS
TO ONE TERMINAL OF STARTING RESISTOR
RELAY COIL
TO LINE
MAIN AIR GAP
1
2
3
TO STARTING RESISTOR
5
4
6
MOVABLE ARMATURE
TO SECOND TERMINAL OF STARTING RESISTOR
9
8
7
AUXILIARY AIRGAP
ARM
SET SCREW
COPPER DAMPER

CIRCUIT
(A)

DETAILS OF CONTACTOR
(B)

Figure 16-21.—Series current-limit starter.

through the coil causes the accelerating contactor to lock open. When the current falls to a certain predetermined value, the switch will close.

The coil is wound with a few turns of heavy wire. When current flows through the coil, the movable armature is acted upon by two forces, one across the main air gap, the other across the auxiliary air gap. The force across the main air gap tends to close the contactor; that across the auxiliary air gap tends to open it. The flux paths are first 1, 2, 3, 4, 5, 6, 1 ; and second 1, 2, 3, 7, 8, 9, 6, 1. The first path includes only the main air gap. The second includes both gaps. When a small amount of current flows through the coil, the flux path is principally through 1, 2, 3, 4, 5, and 6 and the force exerted across the main air gap tends to close the switch. When a large amount of current flows through the coil, the flux path is through 1, 2, 3, 7, 8, and 9. This path includes both the main and auxiliary air gaps. Because the auxiliary gap is smaller, the force exerted across this gap to hold the contactor open exceeds the force across the main gap to close it and the contactor locks open.

To prevent the flux from rushing through the shorter path, 4, 5, 6, and closing the contactor before it has time to lock open, a short-circuited coil (damper) is placed around this flux path, as shown in figure 16-21 (B). As the flux links this coil, the induced current in the copper damper sets up a counter magnetomotive force that opposes the original flux and causes it to take the path through 7, 8, and 9 during the time that the current is rising. When the series operating coil current levels off at a high value, the flux path 4, 5, and 6 becomes saturated and sufficient flux is established through 7, 8, and 9 to maintain the contactor in the locked-out condition.

This type of contactor is especially satisfactory when the motor is always under load. The principal disadvantage is that the switch may drop open on light load. However, a shunt holding coil may be used to prevent this.

Motor Efficiency

The efficiency of any type of machine is the ratio of the output power to the input power. This ratio is commonly expressed as a percent. Because all machines have some losses, the efficiency will never be 100 percent. Expressed as a percentage, efficiency becomes

$$\text{efficiency} = \frac{\text{output}}{\text{input}} \times 100,$$

or

$$\text{efficiency} = \frac{\text{output}}{\text{output} + \text{losses}} \times 100,$$

$$\text{efficiency} = \frac{\text{input} - \text{losses}}{\text{input}} \times 100.$$

The first equation is general. The second is advantageous when applied to electric generators and transformers. The third is most useful when applied to electric motors. The output must be expressed in the same units as the input. For example, if the output is expressed in horsepower and the input is expressed in watts, they can be changed to common units by means of the relation,

$$746 \text{ watts} = 1 \text{ horsepower.}$$

There are various types of mechanical and electrical losses in d-c motors, some of which are common to other types of motors.

One loss is in BEARING FRICTION. This type of friction is reduced by proper oiling. Roller bearings have less friction loss than sleeve bearings. However, at excessive speed or under excessive load the loss due to bearing friction may be appreciable. A loss is also introduced by BRUSH FRICTION. This may be reduced by the use of a well-polished commutator and properly fitted brushes. WINDAGE LOSS is that due to the resistance of the air to a rapidly revolving armature. IRON LOSSES include eddy-current loss and hysteresis in the armature iron. COPPER LOSSES include the I^2R loss in the armature and field windings.

As an example, assume that the motor shown in figure 16-22 is supplied with 10 amperes at 100 volts.

The COPPER LOSS in the field is

$$I_f^2 \times R_f = 1^2 \times 100 = 100 \text{ watts.}$$

The armature current is 10 - 1, or 9 amperes and the COPPER LOSS in the armature is

$$I_a^2 \times R_a = 9^2 \times 1 = 81 \text{ watts.}$$

Assume that the total MECHANICAL LOSS (friction, windage, and so forth) is 90 watts. The TOTAL LOSS is therefore 271 watts.

The input is

$$E_a \times I_L = 100 \times 10 = 1{,}000 \text{ watts.}$$

The output is

$$\text{input} - \text{losses} = 1{,}000 - 271 = 729 \text{ watts.}$$

The efficiency is

$$\frac{\text{output}}{\text{input}} \times 100 = \frac{729}{1{,}000} \times 100 = 72.9 \text{ percent.}$$

If it is determined (by means of a prony brake test) that the power developed by the motor is 0.976 horsepower, the efficiency is also determined as

$$\text{efficiency} = \frac{\text{output}}{\text{input}} \times 100 = \frac{0.976 \times 746}{1{,}000} \times 100 = 72.9 \text{ percent.}$$

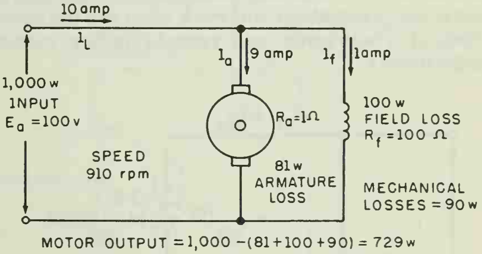


Figure 16-22.—Distribution of losses in a motor.

Speed Control

The speed, N, of a d-c motor is directly proportional to the armature counter e.m.f., E_c, and inversely proportional to the field strength, Φ.

Transposing equation (16-8) for N, $N = \dfrac{E_c 10^8 p}{\Phi Z P}$.

Such factors as the numbers of poles, P, the number of current paths, p, and the total number of armature conductors, Z, can be lumped into a single constant, K. Simplified, the expression becomes

$$\text{r.p.m.} = \frac{KE_c}{\Phi}\ .$$

In a shunt motor

$$E_c = E_a - I_a R_a.$$

and

$$\text{r.p.m.} = \frac{K(E_a - I_aR_a)}{\Phi}\ , \qquad (16\text{-}11)$$

where E_a is the voltage applied across the armature. This is similar to, but not identical with, equation (16-9) for a series motor.

From equation 16-11, it is seen that the speed may be INCREASED by DECREASING the field strength, and vice versa, or the speed may be increased by increasing E_a, and vice versa. Practically, these variations are most simply accomplished by inserting a field rheostat in series with the field circuit, or a variable resistor in series with the armature circuit.

SPEED CONTROL BY ARMATURE SERIES RESISTANCE

Figure 16-23 shows how speed control may be accomplished by means of a variable resistor in series with the armature. The circuit is the same as that used in the motor starter circuit in figure 16-16. However, the wattage rating is different. The starting resistance should only be inserted for a short interval, whereas the speed control resistance can remain in the circuit indefinitely.

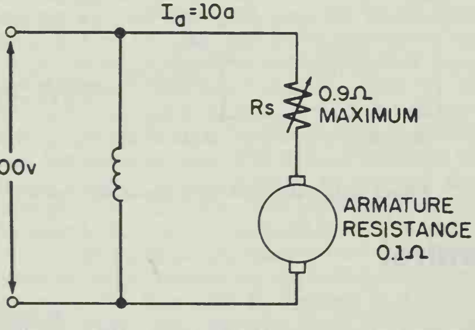


Figure 16-23.—Speed control by means of armature series resistor.

In the example of the motor shown in figure 16-23, assume that $\frac{K}{\Phi}$, as indicated in the previous equation, is replaced by the number 10. The equation for speed in r.p.m. then becomes

$$\text{r.p.m.} = 10\Big[E_a - I_a(R_s - R_a)\Big].$$

When R_s is set at zero, the resistance, R_a, offered by the armature is 0.1 ohm, and I_a is assumed to be 10 amperes. Therefore,

$$\text{r.p.m.} = 10\ [100 - 10(0 + 0.1)] = 990.$$

When R_s is increased to 0.1 ohm, I_a is lowered. The motor speed is reduced, the counter e.m.f. is reduced, and I_a is assumed to come back to the original value of 10 amperes. At the stable condition, the new speed is

$$\text{r.p.m.} = 10\ [\ 100 - 10(0.1 + 0.1)\ ] = 980.$$

The rheostatic losses involved in this method of speed control are appreciable at low speeds and the resultant reduction in efficiency makes this type of control undesirable if the motor is to be operated at greatly reduced speed for prolonged intervals.

SPEED CONTROL BY ADJUSTING THE FIELD STRENGTH

A more economical method of speed control is by rheostatic adjustment of the field current. If the field strength is weakened, the speed of the motor is increased; and if the strength of the field is increased, the speed of the motor is decreased.

Figure 16-24 indicates a method of varying the strength of the field by means of a field rheostat. When the field rheostat is cut out, the field current is 1 ampere. The counter e.m.f. is 90 volts, and the armature current is 10 amperes. The MEASURED speed is 900 r.p.m. When the resistance of the field rheostat is increased to 11.1 ohms, the field current is reduced to 0.9 amperes and the field flux is reduced. This causes a reduction in counter e.m.f. and a sharp increase in armature current, which causes an increase in force on the armature and an increase in armature speed. As the speed builds up, the counter e.m.f. builds up to 90 volts again, and the armature current is again reduced to 10 amperes.

The speed corresponding to a field current of 0.9 ampere may be computed if it is recalled that the speed varies inversely with the flux and that the flux (below saturation) varies directly with the current. Thus, if the speed is 900 r.p.m. when the field current is 1 ampere it will be $900 \times \frac{1}{0.9} = 1{,}000$ r.p.m. when the field current is 0.9 ampere.

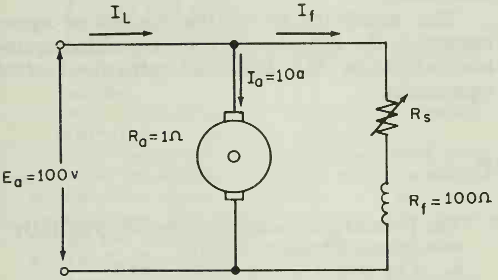

I_L
I_f
I_a=10a
R_s
R_a=1Ω
E_a=100v
R_f=100Ω

Figure 16-24.—Speed control by varying the strength of the field.

SPEED CONTROL BY WARD-LEONARD SYSTEM

As has been explained in the previous paragraphs, the speed of a d-c motor can be controlled by at least two methods—either the armature voltage can be varied, as in figure 16-23 or the field voltage can be varied as in figure 16-24. The first method gives a range of speeds below the rated full-load speed. The second, gives a range of speed above the rated full-load speed. The first method takes away the constant speed characteristics from the shunt motor when the load varies. The second method permits control with a physically smaller resistor and greatly reduced power and gives essentially constant speed characteristics at any speed setting of the field rheostat provided the field is not weakened excessively. With a very weak field the motor may stall. The inherent difficulties of both methods are removed by the Ward-Leonard method shown in figure 16-25.

The d-c motor armature whose speed is to be controlled, is fed directly from a d-c generator armature which is driven by a constant-speed

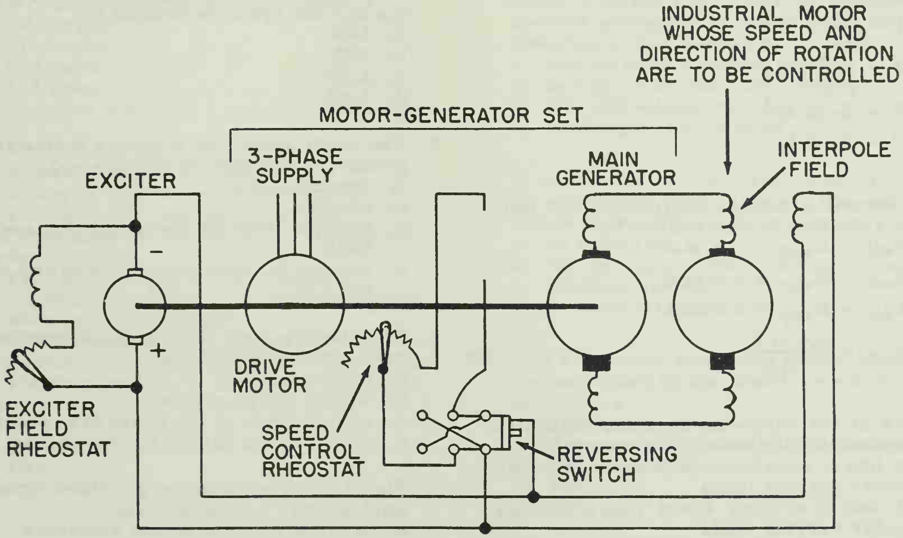

INDUSTRIAL MOTOR WHOSE SPEED AND DIRECTION OF ROTATION ARE TO BE CONTROLLED
MOTOR-GENERATOR SET
3-PHASE SUPPLY
EXCITER
MAIN GENERATOR
INTERPOLE FIELD
-
+
DRIVE MOTOR
EXCITER FIELD RHEOSTAT
SPEED CONTROL RHEOSTAT
REVERSING SWITCH

Figure 16-25.—Ward-Leonard speed control system.

prime mover. The d-c field supply to the generator is variable in both magnitude and polarity by means of a rheostat and reversing switch, as shown. Therefore, the motor armature is supplied by a generator having smoothly varying voltage output from zero to full-load value. The motor field is supplied with a constant voltage from the same source as that supplying the generator fields. The generator drive power could be from a single-phase or three-phase a-c motor, from an engine, or other constant-speed source. In the same way, the d-c supply can be supplied from a rectifier, from an exciter on the end of the generator shaft, or from any other suitable d-c source. In the figure the field exciter is a direct-connected unit on the shaft of the motor-generator set. The drive motor for the M-G (MOTOR-GENERATOR) set is shown as a 3-phase motor. Both the main generator and the speed-control motor have commutating poles, and in some instances, compensating windings.

The advantages of this type of speed control are that it does away with the armature rheostatic losses and instability of speed with variable loads.

The disadvantage of this method of speed control is the initial expense of the added equipment—that is, the M-G set with its control equipment.

QUIZ

1. The most convenient method of determining the direction of induced motion of a current-carrying conductor in a magnetic field is by
   a. applying the right-hand rule for motors
   b. applying the left-hand rule for motors
   c. using a small permament magnet
   d. observation of the location of the conductor

2. The formula tor torque developed by a motor is
   a. $T = \frac{K_t}{\Phi I_a}$
   b. $T = K_t^2 \ \Phi \ I_a$
   c. $T = K_t \ \Phi \ I_a^2$
   d. $T = K_t \ \Phi \ I_a$

3. The effective voltage (E_{eff}) drop in a motor's armature is determined by
   a. $E_{eff} = E_{app} + \text{c.e.m.f.}$
   b. $E_{eff} = E_{app} \times \text{c.e.m.f.}$
   c. $E_{eff} = E_{app} - \text{c.e.m.f.}$
   d. $E_{eff} = \frac{\text{c.e.m.f.}}{E_{app}}$

4. Which of the following is true, regarding the speed regulation of a shunt motor?
   a. It has a constant-speed characteristic under varying loads
   b. It has a varying speed characteristic under varying loads
   c. It has a varying speed characteristic under constant loads
   d. None of the above are correct

5. The primary advantage of the differentially compounded motor is that
   a. it is stable under heavy loads
   b. its speed regulation is very good if load is not excessive
   c. it has good speed regulation under varying loads
   d. it will start under a heavy load

6. If the no-load speed of a shunt motor is 1,800 r.p.m. and the full-load speed is 1,475 r.p.m., the speed regulation is
   a. 18%
   b. 22%
   c. 2.2%
   d. 1.8%

7. The input power of a series motor is the product of the applied voltage and
   a. counter e.m.f.
   b. torque
   c. current through the armature and the field
   d. current through the armature and counter e.m.f.

8. The disadvantage of the time-element automatic starter is that the
   a. cost is high
   b. wiring is complicated
   c. construction is too heavy to be practical
   d. motor is not protected on overload

9. The starting resistor of the shunt current-limit starter is connected in
   a. parallel with the motor armature
   b. series with the accelerating contactor
   c. series with the field winding of the motor
   d. series with the armature of the motor

10. A motor which has an output of 820 watts and an input of 960 watts has an efficiency of approximately
   a. 90%
   b. 85%
   c. 75%
   d. 70%
11. The horsepower developed by a motor depends mainly upon which of the following two factors?
   a. Speed and voltage
   b. Speed and torque
   c. Torque and voltage
   d. Torque and watts
12. A series motor is more adaptable where a
   a. small variation of torque and speed is needed
   b. wide variation of torque but a small variation of speed is needed
   c. wide variation of torque is required, and wide variations in speed are allowable
   d. constant speed is needed
13. Cumulative compound motors are best suited for use where
   a. small starting torque is required
   b. small changes in speed can be tolerated
   c. the load may be removed from the motor with safety
   d. constant speed under varying load is required
14. What is the output power in watts of a shunt motor of 1 horsepower operating on 100 volts at 910 r.p.m., armature current of 9 amps., and a line current of 10 amps.?
   a. 98.4 watts
   b. 472 watts
   c. 646 watts
   d. 815 watts
15. The counter e.m.f. of a motor is zero when the
   a. motor is at rated speed
   b. armature is not turning
   c. motor is almost up to rated speed
   d. armature has just begun to turn
16. The operation of the c.e.m.f. starter depends upon the
   a. size of the orifice in the dashpot
   b. c.e.m.f. developed across the armature
   c. accelerating contacts
   d. interlocking relays
17. In a shunt current-limit starter the number of starting resistors that are commonly used is
   a. one
   b. two or three
   c. five or six
   d. more than ten
18. The speed of a motor with no load, with an increase of resistance in series with the field winding, will
   a. not be affected
   b. decrease
   c. increase
   d. fluctuate rapidly
19. The generated voltage (c.e.m.f.) of a motor
   a. opposes the impressed (source) voltage
   b. opposes any change in load
   c. aids the impressed (source) voltage
   d. none of the above are correct
20. When a load is applied to a shunt motor, which one of the following will happen?
   a. Speed decreases—c.e.m.f. goes up
   b. Speed increases—c.e.m.f. goes down
   c. Speed increases—c.e.m.f. goes up
   d. Speed decreases—c.e.m.f. goes down
21. On a time-element starter what determines the speed with which the resistance is cut out?
   a. Size of the orifice in the dashpot
   b. Counter e.m.f. of the armature
   c. Interlocking relays
   d. Accelerating contacts
22. The coil of the accelerating contactor of the shunt current-limit starter is caused to become energized by which of the following when the motor speeds up?
   a. Series relay contacts closing
   b. Series relay contacts opening
   c. The no-voltage release
   d. Holding relay contacts
23. In the series current-limit starter the flux is prevented from closing the contactor before it has time to lock open by
   a. an open coil
   b. the spring tension of the contacts
   c. starting resistor
   d. a short-circuited coil
24. The d-c motor armature whose speed is to be controlled by the Ward-Leonard system is fed by a
   a. 3-phase motor
   b. d-c supply in parallel with a rheostat
   c. d-c generator
   d. rectifier

CHAPTER 17

ALTERNATING-CURRENT INSTRUMENTS

In chapter 16, the simpler electrical indicating instruments were discussed. Only a few could measure a.c. Most were used to measure only direct voltage or current. It will be necessary for the technician to become familiar with additional, more advanced a-c indicating instruments. Those that will be discussed in this chapter are (1) rectifier-type a-c meters; (2) wattmeters and watt-hour meters, (3) instrument transformers; (4) bridge meters for measuring resistance, voltage, current, capacitance, and inductance; (5) frequency meters; and (6) the single-phase power-factor meter.

Many of the instruments discussed in this chapter utilize metallic rectifiers. Since these units are common to a number of different instruments, they will be discussed first.

Metallic Rectifiers

A metallic rectifier is a device that offers a high opposition to current flow through it in one direction but not in the other. It is therefore effectively a unidirectional conductor and is used mostly for converting alternating current into a unidirectional current (direct current).

A metallic rectifier element, called a cell, consists of a good conductor and a semiconductor (material of high resistivity) separated by a thin insulating barrier layer. The flow of forward current through a cell consists of a flow of electrons from the good conductor, across the barrier layer, and through the semiconductor.

Metallic rectifier cells are usually made in the form of plates, circular or square in shape, with a hole in the center. A number of cells, with the necessary terminals, spacers, and washers, are assembled on an insulated stud passing through their center holes. This assembly is called a rectifier stack. Some assemblies contain fins, which are used to keep the rectifier from overheating; they afford a large surface area for conducting away the heat. Cells and stacks may be connected in series or parallel, with proper polarities, to obtain the required voltage and current ratings and circuit connections for specific applications.

Two types of metallic rectifiers are used in the Navy—(1) a thin film of copper oxide and copper, and (2) selenium and either iron or aluminum. Metallic rectifier units are represented by the symbol shown in figure 17-1 (A). The arrowhead in the symbol points against the direction of electron flow.

Figure 17-1 (B) shows a simple a-c circuit that utilizes a metallic rectifier. It rectifies the a-c voltage and produces a series of d-c voltage pulses as its output. Although the copper-oxide rectifier is shown, the selenium rectifier may be used instead.

In the copper-oxide rectifier shown in figure 17-2 (A), the oxide is formed on the copper disk before the rectifier unit is assembled. In this type of rectifier the electrons flow more readily from the copper to the oxide than from the oxide to the copper. External electrical connections may be made by connecting terminal lugs between the left pressure plate and the copper and between the right pressure plate and the lead washer.

For the rectifier to function properly, the oxide coating must be very thin. Thus, each individual unit can stand only a low inverse voltage. Rectifiers designed for moderate and high-power applications consist of many of these individual units mounted in series on a single support. The lead washer enables uniform pressure to be applied to the units so that the internal resistance may be reduced. When the units are connected in series, they normally present a

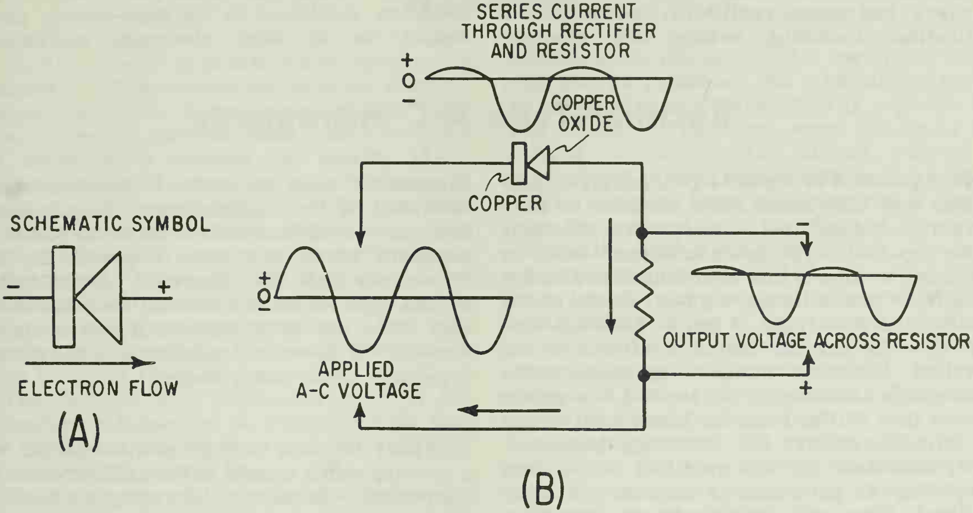

SCHEMATIC SYMBOL
−
+
ELECTRON FLOW
(A)
SERIES CURRENT THROUGH RECTIFIER AND RESISTOR
+
0
−
COPPER OXIDE
COPPER
+
0
−
APPLIED A-C VOLTAGE
−
OUTPUT VOLTAGE ACROSS RESISTOR
+
(B)

Figure 17-1.—(A) Metallic rectifier symbol; (B) waveforms in simple a-c circuit utilizing a rectifier.

relatively high resistance to the current flow. The resultant heat developed in the resistance must be removed if the rectifier is to operate satisfactorily. Many commercial rectifiers have copper fins between each unit for the purpose of dissipating the excess heat. The useful life of the unit is extended by keeping the temperature low (below 140°F.). The efficiency of this type of rectifier is generally between 60 and 70 percent.

Selenium rectifiers function in much the same manner as copper-oxide rectifiers. A selenium rectifier is shown in figure 17-2 (B). Such a rectifier is made up of an iron disk that is coated with a thin layer of selenium. In this type of rectifier the electrons flow more easily from the selenium to the iron than from the iron to the selenium.

Commercial selenium rectifier units are designed to pass 50 milliamperes per square centimeter of plate area. This type of rectifier may be operated at a somewhat higher temperature than a copper-oxide rectifier of similar rating. The efficiency is between 65 and 85 percent, depending on the circuit and the loading. As in the case of the copper-oxide rectifier, any practical number of units may be bolted together in series to increase the voltage rating. Larger element disks and the necessary cooling fins may be used for higher current ratings. Also, forced-air cooling may be used.

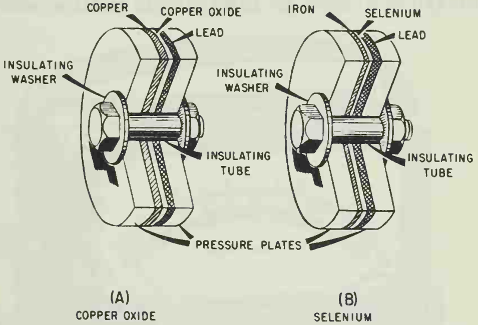

COPPER
COPPER OXIDE
LEAD
INSULATING WASHER
INSULATING TUBE
IRON
SELENIUM
LEAD
INSULATING WASHER
INSULATING TUBE
PRESSURE PLATES
(A)
COPPER OXIDE
(B)
SELENIUM

Figure 17-2.—Metallic rectifier construction.

Metallic rectifiers may be used not only as half-wave rectifiers, as shown in figure 17-1, but also in full-wave and bridge circuits. In each of these applications the action of the metallic rectifier is similar to that of a diode.

Metallic rectifiers may be used in battery chargers, instrument rectifiers, and many other applications including welding and electroplating. Commercial radios also frequently use selenium rectifiers in the high-voltage power supply, as do other electronic equipments.

Rectifier-Type A-C Instruments

It is possible to connect a D'Arsonval direct-current type instrument and a rectifier so as to measure a-c quantities. The rectifier is usually of the dry-plate type (such as copper-oxide or selenium rectifiers) and is arranged in a bridge circuit, as shown in figure 17-3. By the use of rectifiers in the bridge, it can be seen that current flow through the meter is always in one direction. When the voltage being measured has a waveform as shown in figure 17-3, the path of current flow will be from the lower input terminal through rectifier No. 3 through the instrument, and then through rectifier No. 2, thus completing its path back to the source's upper terminal. The next half cycle of the input voltage (indicated by dotted sine wave) will cause the current to pass through rectifier No. 1, through the instrument, and through rectifier No. 4, completing its path back to the source.

This type of instrument generally is characterized by errors due to waveform and frequency. Allowances must be made, according to data furnished by the manufacturer. It is possible, however, to add corrective networks to the instrument which will make it practically free from error up to 100 kilocycles. An instrument of this type requires a current from the line of only about one milliampere for full scale deflection. It is widely used for a-c voltmeters, especially of the lower ranges.

There is some ''aging'' of the rectifier with a corresponding change in the calibration of the instrument. Because of this aging such instruments must be recalibrated from time to time. A rectifier-type instrument reads the average value of the a-c quantity. However, because the EFFECTIVE, or root-meansquare (r. m. s.), values are more useful, a-c meters are generally calibrated to read r.m.s. values (1.11 times the average of the instantaneous values).

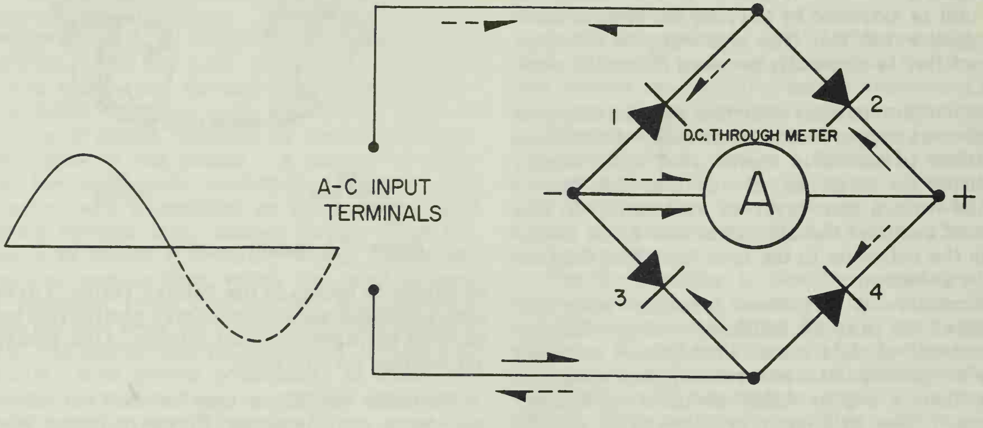


Figure 17-3.—Simple connection of a full-wave, rectifier-type, a-c instrument.

Wattmeter

Electric power is measured by means of a wattmeter. This instrument is of the electrodynamometer type. It consists of a pair of fixed coils, known as current coils, and a movable coil, known as the potential coil. (See fig. 17-4.) The fixed coils are made up of a few turns of comparatively large conductor. The potential coil consists of many turns of fine wire; it is mounted on a shaft, carried in jeweled bearings, so that it may turn inside the stationary coils. The movable coil carries a needle which moves over a suitably graduated scale. Flat coil springs hold the needle to a zero position, as shown in figure 16-10 of chapter 16.

The current coil (stationary coil) of the wattmeter is connected in series with the circuit (load), and the potential coil (movable coil) is connected across the line.

When line current flows through the current coil of a wattmeter, a field is set up around the coil. The strength of this field is proportional to the line current and in phase with it. The potential coil of the wattmeter generally has a high resistance resistor connected in series with it. This is for the purpose of making the potential-coil circuit of the meter as purely resistive as possible. As a result, current in the potential circuit is practically in phase with line voltage. Therefore, when voltage is impressed on the potential circuit, current is proportional to and in phase with the line voltage.

The actuating force of a wattmeter is derived from the interaction of the field of its current coil and the field of its potential coil. The force acting on the movable coil at any instant (tending to turn it) is proportional to the product of the instantaneous values of line current and voltage.

The wattmeter consists of two circuits, either of which will be damaged if too much current is passed through them. This fact is to be especially emphasized in the case of wattmeters, because the reading of the instrument does not serve to tell the user that the coils are being overheated. If an ammeter or voltmeter is overloaded, the pointer will be indicating beyond the upper limit of its scale. In the wattmeter, both the current and potential circuits may be carrying such an overload that their insulation is burning, and yet the pointer may be only part way up the scale. This is

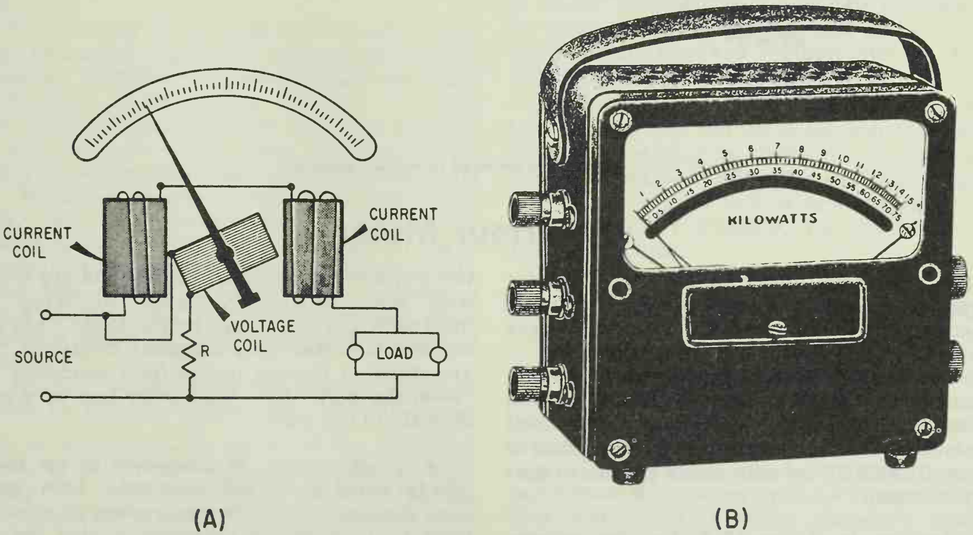
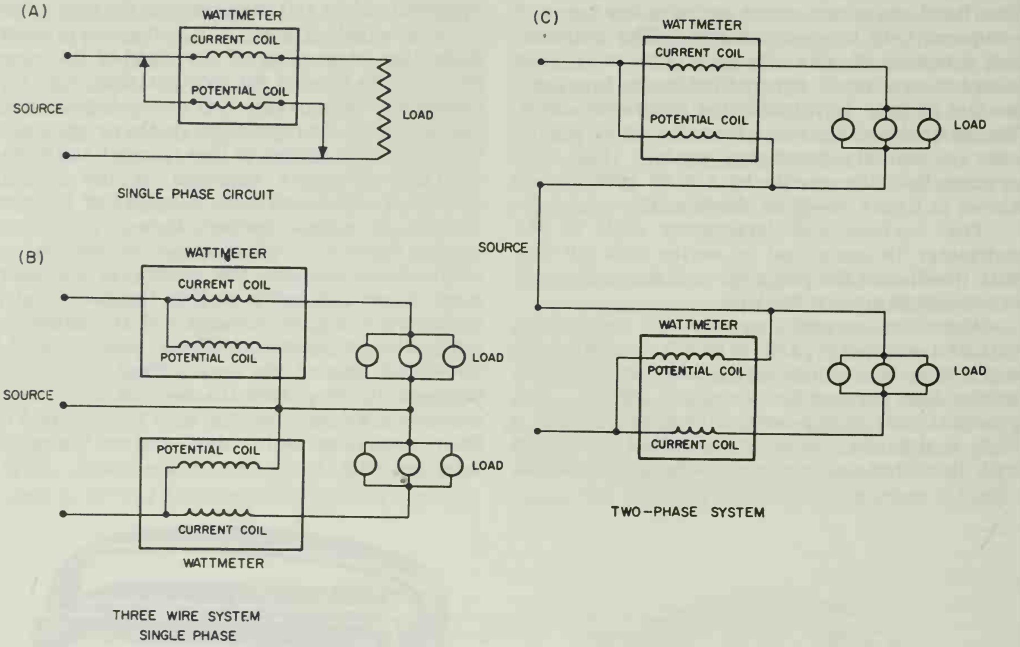


Figure 17-4.—Simplified electrodynamomter wattmeter circuit.

because the position of the pointer depends upon the power factor of the circuit as well as upon the voltage and current. Thus, a low power-factor circuit will give a very low reading on the wattmeter even when the current and potential circuits are loaded to the maximum safe limit. This safe rating is generally given on the face of the instrument.

A wattmeter is always distinctly rated, not in watts but in volts and amperes.

Figure 17-5 shows the proper way to connect a wattmeter in various circuits.


(A)
WATTMETER
CURRENT COIL
POTENTIAL COIL
SOURCE
LOAD
(B)
WATTMETER
CURRENT COIL
POTENTIAL COIL
SOURCE
LOAD
POTENTIAL COIL
LOAD
CURRENT COIL
WATTMETER
(C)
WATTMETER
CURRENT COIL
POTENTIAL COIL
LOAD
SOURCE
WATTMETER
POTENTIAL COIL
LOAD
CURRENT COIL

SINGLE PHASE CIRCUIT

THREE WIRE SYSTEM
SINGLE PHASE

TWO-PHASE SYSTEM

Figure 17-5.—Wattmeter connected in various circuits.

Watt-Hour Meter

The watt-hour meter is an instrument for measuring energy. As energy is the product of power and time; the watt-hour meter must take into consideration both of these factors.

In principle, the watt-hour meter is a small motor whose instantaneous speed is proportional to the POWER passing through it. The total revolutions in a given time are proportional to the total ENERGY or watt-hours consumed during that time.

Referring to figure 17-6, the line is connected to two terminals on the left-hand side of the meter. The upper terminal is connected to two coils *FF* in series. These coils are wound with wire sufficiently large to carry the maximum current taken by the load. They are connected so that their magnetic fields add. The armature *A* rotates in the field produced between the coils *FF*. The other line wire goes directly to the load.

A shunt circuit is connected to the upper line terminal on the left-hand side. This circuit runs through coil *F'*, to the brushes *B*, commutator *C*, through the armature *A*, and the resistor *R*, to the return line. (The resistor is omitted in some watt-hour meters.)

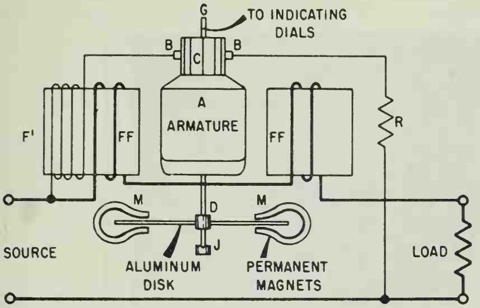


Figure 17-6.—Internal connections of watt-hour meter.

Since the load current is through coils *FF* and there is no iron in the circuit, the magnetic field produced by these coils is proportional to the LOAD CURRENT. The armature, in series with a resistance, is connected directly across the line. The current in the meter armature is proportional to the LINE VOLTAGE. Neglecting the small voltage drop in *FF*, the torque acting on the armature must be proportional to the product of the load current and the load voltage. In other words, it must be proportional to the power passing through the meter to the load.

If the meter is to register correctly, there must be a retarding torque acting on the moving element. This force is proportional to the speed of rotation of the moving element. To meet this condition, an aluminum disk *D* is mounted on the armature shaft. This disk rotates between the poles of two permanent magnets *M* and *M*. In cutting the field produced by these magnets, eddy currents are induced in the disk, retarding its motion. The strength of these currents is proportional to the angular velocity of the disk. Since they are acting in conjunction with a magnetic field of constant strength, their retarding effect is proportional to the speed of rotation.

Friction produced by the rotating element cannot be entirely eliminated. Near the rated load of the meter, the effect of the frictional torque is practically negligible. But, at light loads, the friction torque, which is nearly constant at all loads, is a much greater percentage of the load torque. Since the ordinary meter may operate at light loads during a considerable portion of the time, it is desirable that the error due to friction be eliminated. This is accomplished by means of coil *F'*, which is connected in series with the armature. Coil *F'* is connected so that its field acts in the same direction as that of coils *FF*. Therefore, it assists armature *A* to rotate. Since it is connected in the shunt circuit, it acts continuously. The coil is movable and its position can be adjusted so that the friction error is eliminated.

To reduce friction and wear, the rotating element of the meter is made as light as practical. The element rests on a jewel bearing *J*. This bearing is a sapphire in the smaller types, and a diamond in the larger types of meters. The jewel is supported on a spring. A hardened steel pivot rests in the jewel. In time, the pivot becomes dulled and the jewel roughened, which increases friction and causes the meter to register low unless *F'* is readjusted. The moving element drives the clockwork of the meter through shaft *G*.

The following directions should be followed when reading the dials of a watt-hour meter. The meter, in this case, is a four-dial type.

The pointer on the right-hand dial (fig. 17-7) registers 1 kw.-hr. or 1,000 watt-hours for each division on the dial. A complete revolution of the hand on this dial will move the hand of the second dial one division and register 10 kw.-hr. or 10,000 watt-hours. A complete revolution of the hand of the second dial will move the third hand one division and register 100 kw.-hr. or 100,000 watt-hours, and so on.

Accordingly, you must read the hands from left to right, and add three zeros to the reading of the lowest dial to obtain the reading of the meter in watt-hours. The dial hands should always be read as indicating the figure which they have LAST PASSED, and not the one they are approaching.

SINGLE-PHASE INDUCTION WATT-HOUR METER

As in the case of series motors, the Thompson watt-hour meter may be used with alternating or direct current because both the armature and the field flux reverse at the same time, and the armature continues to rotate in the same direction. The induction watt-hour meter, however, has certain advantages over the Thompson watt-hour meter and is more commonly used to measure a-c power.

The SINGLE-PHASE INDUCTION WATT-HOUR METER includes a simple induction-drive

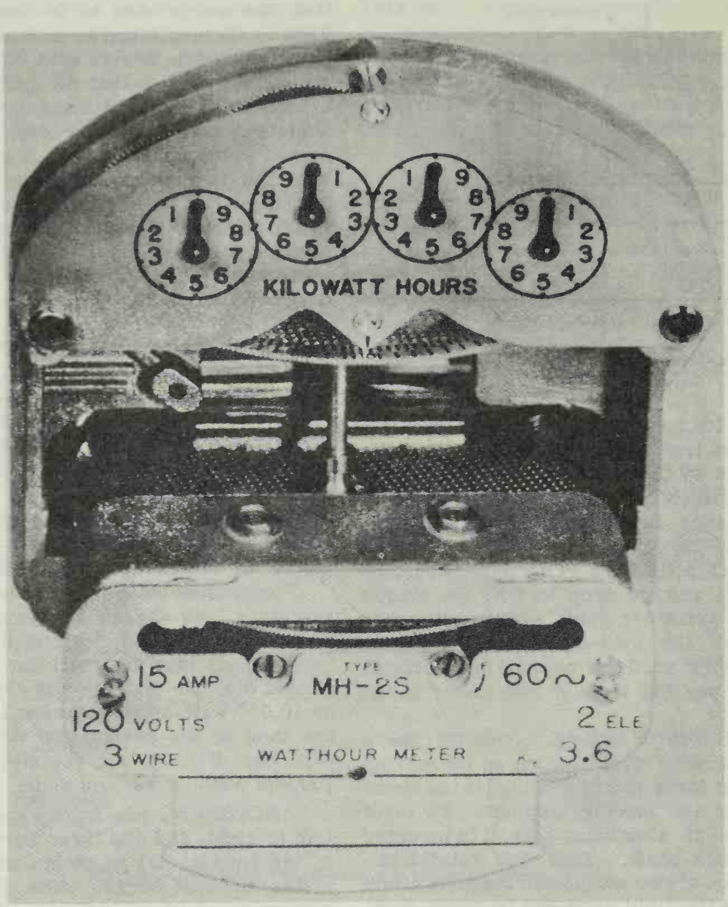
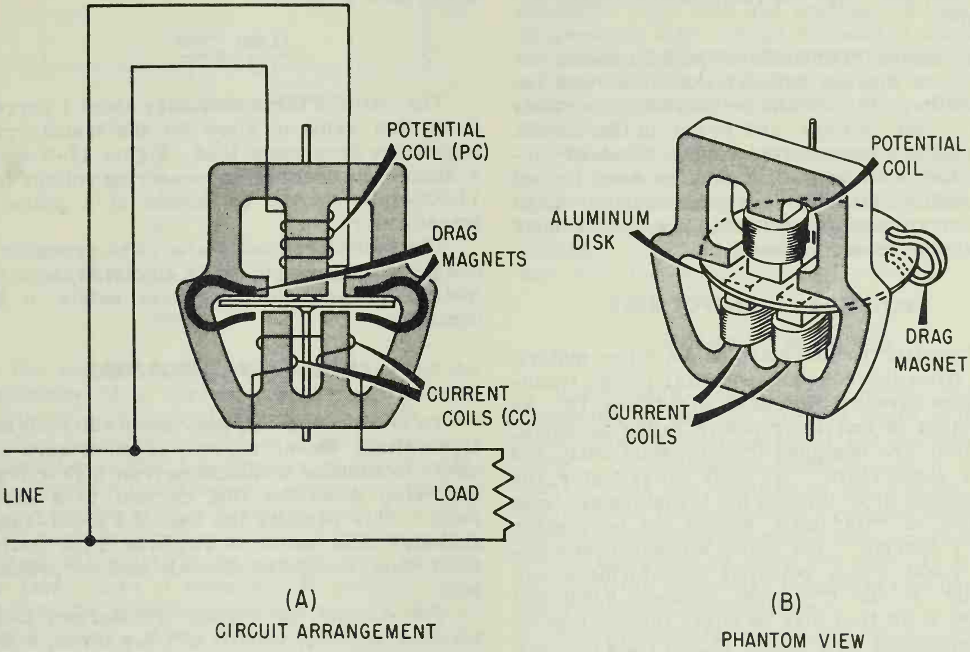


Figure 17-7.—Reading a watt-hour meter.

motor consisting of an aluminum disk, moving magnetic field, drag magnets, current and potential coils, integrating dials, and associated gears. A simplified sketch of an induction watt-hour meter is shown in figure 17-8 (A). The potential coil connected across the load is composed of many turns of relatively small wire. It is wound on one leg of the laminated magnetic circuit. Because of its many turns, the potential coil has high impedance and high inductance, and therefore, the current through it lags the applied voltage by nearly 90°. The two current coils connected in series with the load are composed of a few turns of heavy wire. They are wound on two legs of the laminated magnetic circuit. Because of the few turns, the current coils have low inductance and low impedance.

The arrangement of the potential coil, the aluminum disk, the current coils, and one of the drag magnets is shown in the phantom view (fig. 17-8 (B)).

The rotating aluminum disk is the moving member that causes the gears to turn and the dials to indicate the amount of energy passed through the meter. This rotation of the aluminum disk is accomplished by eddy currents that are



(A)
CIRCUIT ARRANGEMENT

(B)
PHANTOM VIEW

Figure 17-8.—Simplified sketch of an induction watt-hour meter.

established by the current coils and the potential coil. The speed of rotation of the aluminum disk is proportional to the true power supplied through the line to the load. The total energy supplied to the load is proportional to the number of revolutions of the disk during a given period of time.

A small copper shading disk (not shown in the figure) is placed under a portion of the potential pole face. It is in an adjustable mounting and is used to develop a torque in the disk to counteract static friction. The disk has the effect of a shading pole and provides a light-load adjustment for the meter.

The two drag magnets supply the counter torque against which the aluminum disk acts when it turns. The drag is increased (speed of motor is reduced) by moving the magnets toward the edge of the disk. Conversely, the drag is decreased and the speed is increased by moving the magnets toward the center of the disk. Adjustment of the drag magnets will only be made by an authorized instrument and meter technician.

Instrument Transformers

ELECTRICAL MEASUREMENTS AT HIGH VOLTAGES

It is not usually practical to connect instruments and meters directly to high-voltage circuits. Unless the high-voltage circuit is grounded at the instrument, a dangerously high potential-to-ground voltage may exist at the instrument or switchboard. Further, instruments become inaccurate when connected directly to a high voltage, because of the electrostatic forces that act on the indicating element. Specially designed instruments may be constructed so that they can be connected directly to high-voltage circuits, but these instruments are usually expensive.

By means of instrument transformers, instruments may be entirely insulated from the high-voltage circuit and yet indicate accurately the current, voltage, and power in the circuit. Low-voltage instruments having standard current and voltage ranges may be used for all high-voltage circuits, irrespective of the voltage and current ratings of the circuits, if instrument transformers are utilized.

POTENTIAL TRANSFORMERS

Potential transformers do not differ materially from the constant-potential power transformers already discussed in chapter 12. An exception is that their power rating is small, and they are designed for minimum ratio and phase angle error. At unity power factor, the impedance drop through the transformer, from no-load to rated-load, should not be greater than 1 percent. For taking measurements below 5,000 volts, potential transformers are usually of the dry type; between 5,000 and 13,800 volts they may be either the dry type or oil immersed, and above 13,800 volts they are oil-immersed.

Since only instruments, meters, and sometimes indicator lights are ordinarily connected to the secondaries of potential transformers, they have ratings from 40 to 500 watts. For primary voltages of 34,500 volts and higher, the secondaries are rated at 115 volts. For primary voltages less than 34,500 volts, the secondaries are rated at 120 volts. For example, a 14,400-volt potential transformer would have a ratio of

$$\frac{14,400}{120} = \frac{120}{1}$$

The ratio of turns may vary about 1 percent from this value to allow for the transformer impedance drop under load. Figure 17-9 shows a simple connection for measuring voltage in a 14,000-volt circuit by means of a potential transformer.

The secondary should always be grounded at one point to eliminate static electricity from the instrument and to insure the safety of the operator.

CURRENT TRANSFORMERS

To avoid connecting instruments directly into high-voltage lines, current transformers are used. In addition to insulating from high voltage, they step down the line current in a known ratio. This permits the use of a lower-range ammeter than would be required if the instrument were connected directly into the primary line.

The current, or series, transformer has a primary winding, usually of a few turns, wound on a core and connected in series with the line. Figure 17-10 shows a simple connection for measuring current in a 14,400-volt circuit by means of a current transformer.

The secondary windings of practically all current transformers are rated at 5 amperes regardless of the primary current rating. For example, a 2,000-ampere current transformer has a ratio of 400 to 1, and 50-ampere transformer has a ratio of 12 to 1.

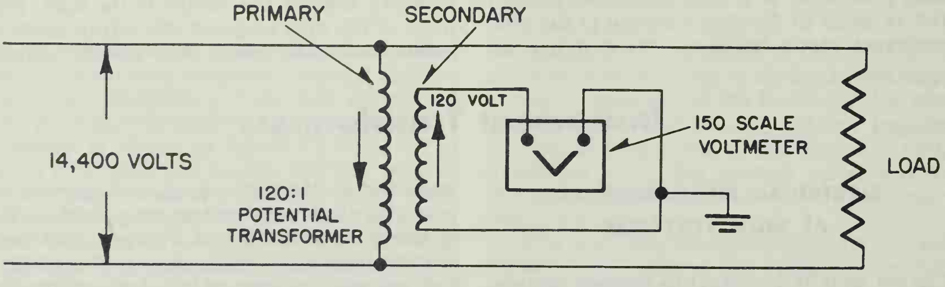


Figure 17-9.—Connections of a potential transformer to a 14,400-volt circuit.

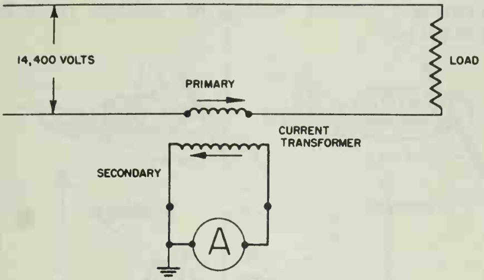


Figure 17-10.—Connections of a current transformer in a 14,400-volt circuit to measure current.

The insulation between the primary and the secondary of a current transformer must be sufficient to withstand full circuit voltage. The current transformer differs from the ordinary constant-potential transformer in that its primary current is determined entirely by the load on the system and not by its own secondary load. If its secondary becomes open-circuited, a high voltage will exist across the secondary, because the large ratio of secondary to primary turns causes the transformer to act as a step-up transformer. Also, since the effects of the counter-ampere-turns of the secondary no longer exist, the flux in the core will depend on the total primary ampere-turns acting alone. This causes a large increase in the flux, producing excessive core loss and heating, as well as a dangerously high voltage across the secondary terminals. THEREFORE, THE SECONDARY OF A CURRENT TRANSFORMER SHOULD NOT BE OPEN-CIRCUITED UNDER ANY CIRCUMSTANCES.

Figure 17-11 shows the method of connecting a complete instrument load, through instrument transformers, to a high-voltage line. The load on the instrument transformers includes an ammeter *A*, a voltmeter *V*, a wattmeter, and a watt-hour meter.

POLARITY MARKING

Instruments, meters, and relays must be connected so that the correct phase relations exist between their potential and current circuits. In instrument transformers it is important that the relation of the instantaneous polarities of the secondary terminals to the primary terminals be known. It has become standard to designate or mark the primary terminals and the secondary terminals that have the same instantaneous polarity.

The primary terminals are marked *H*1, *H*2, etc., and the secondary terminals *X*1, *X*2, etc. In a wiring diagram, primary and secondary

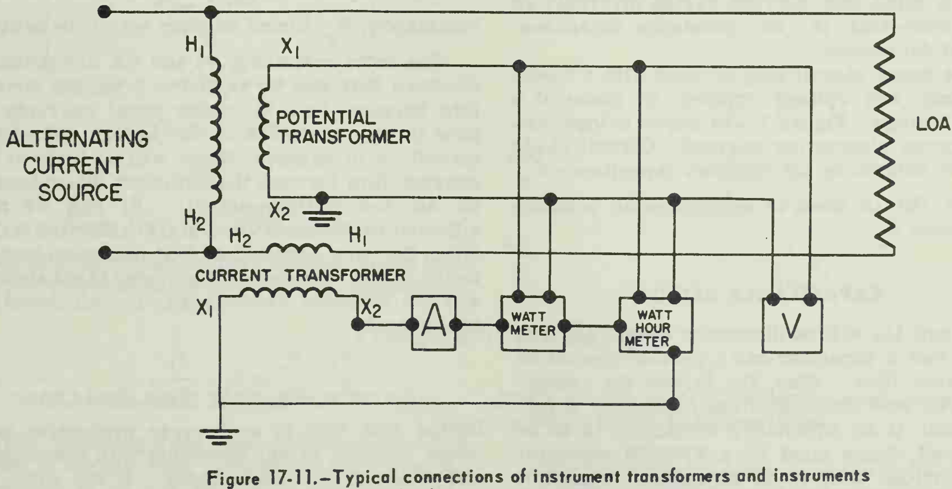


Figure 17-11.—Typical connections of instrument transformers and instruments for single-phase measurements.

terminals having the same instantaneous polarity are marked with a dot. This is shown in figure 17-11.

HOOK-ON TYPE VOLTAMMETER

The hook-on a-c ammeter consists essentially of a current transformer with a split core and a rectifier-type instrument connected to the secondary. The primary of the current transformer is the conductor through which the current to be measured flows. The split core permits the instrument to be "hooked on" the conductor without disconnecting it. Therefore the current flowing through the conductor may be measured safely with a minimum of inconvenience, as shown in figure 17-12.

The instrument is usually constructed so that voltages also may be measured. However, in order to read voltage, the meter switch must be set to VOLTS, and leads must be connected from the voltage terminals on the meter to the terminals across which the voltage is to be measured.

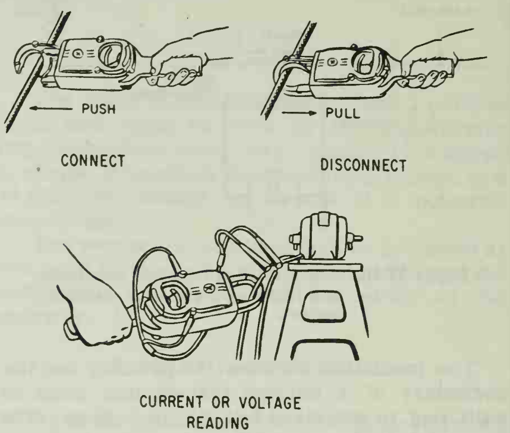


Figure 17-12.—Hook-on type voltammeter.

A-C Bridges

D-c bridges, called Wheatstone bridges, are covered in chapter 5. Before continuing this section on a-c bridges you should review bridge principles given in chapter 5. Notice particularly the ratio method of determining an unknown value that forms one leg of a bridge. Keep in mind that current varies inversely as resistance—that is, as resistance increases, current decreases.

The same circuit may be used with a fixed-frequency a-c voltage applied, in place of a direct voltage. Figure 17-13 shows bridge circuits using alternating current. Circuit (A) is used to determine an unknown capacitance C_x. Circuit (B) is used to determine an unknown inductance L_x.

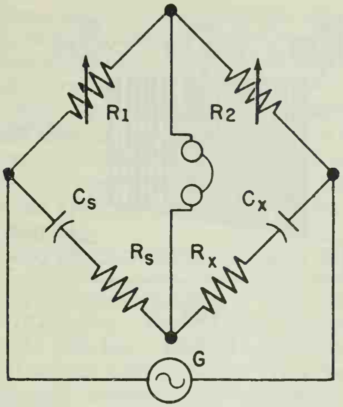
CAPACITANCE BRIDGE

Circuit (A) will be discussed first. You will recall that a capacitor has a certain opposition to current flow. Also, the larger its capacitance the less its opposition becomes. It follows that if an UNKNOWN capacitor is to be measured, there must be a KNOWN capacitor in the bridge with which the unknown capacitor may be compared, as shown in figure 17-13 (A). C_s is the capacitor whose value is known. The resistance of C_s is shown as an equivalent resistance, R_s. This capacitor (with its series resistance) forms one leg of the bridge. The unknown capacitor, C_x, along with its unknown resistance, R_x, forms another leg of the bridge.

The ratio resistors, $R1$ and $R2$, are potentiometers that can be varied to bring the circuit into balance—that is, cause equal currents to flow in the two sides of the bridge. When the circuit is in balance, there will be little or no current flow through the indicator (headphones, or an a-c milliammeter). $R1$ and $R2$ are adjusted by means of accurately calibrated dials. When they are adjusted so that minimum hum is heard in the headphones, the bridge is in balance, and the unknown capacity may be calculated by the formula:

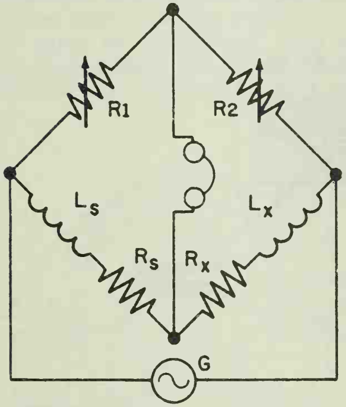
$$\frac{R_1}{R_2} = \frac{C_x}{C_s} \text{ or } C_x = \frac{R_1}{R_2} \times C_s .$$

Notice that this is an inverse proportion because current varies inversely with resistance and directly with capacitance. If the ratio of reactance to resistance is the same in the legs



CAPACITANCE BRIDGE

(A)



INDUCTANCE BRIDGE

(B)

Figure 17-13.—A-C bridge circuits.

containing capacitance, the following direct proportion exists between the resistive components:

$$\frac{R_1}{R_2} = \frac{R_s}{R_x}$$

$$R_x = \frac{R_2}{R_1} \times R_s$$

Thus, the unknown resistance and capacitance, R_x, and C_x, can be estimated in terms of the known resistances, R_1, R_2, and R_s, and the known capacitance, C_s.

INDUCTANCE BRIDGE

The value of an unknown inductance may be determined in the same manner as an unknown capacitance, as shown in figure 17-13 (B). You will recall that an inductor also has a certain opposition to current flow. Also, the larger the inductance, the greater becomes its opposition. To measure an UNKNOWN inductance (L_x) in a bridge circuit, there must be an inductor of KNOWN VALUE (L_s). This known inductor is compared with the unknown inductor.

The ratio resistors, $R1$ and $R2$, are potentiometers that can be varied to bring the circuit into balance. When there is minimum hum in the headphones, the bridge is said to be in balance, and the unknown inductance may be calculated by the formula:

$$\frac{R_1}{R_2} = \frac{L_s}{L_x},$$

or

$$L_x = \frac{R_2}{R_1} L_s;$$

and

$$\frac{R_1}{R_2} = \frac{R_s}{R_x}$$

or

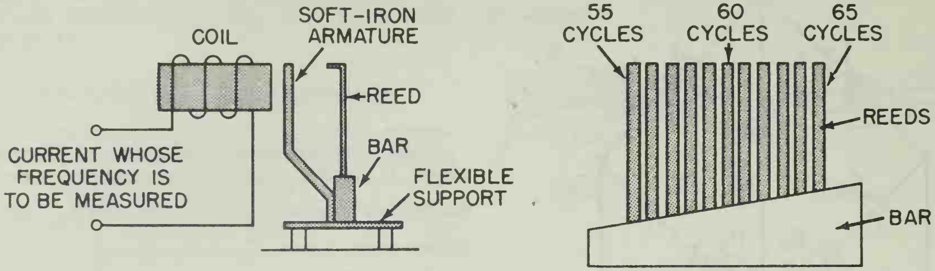
$$R_x = \frac{R_2}{R_1} R_s .$$

Frequency Meters

VIBRATING-REED FREQUENCY METER

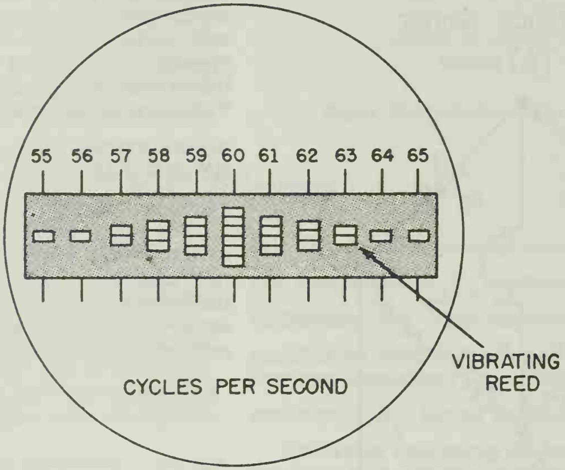
The vibrating-reed type of frequency meter is one of the simplest devices for indicating the frequency of an a-c source. A simplified diagram of one type of vibrating-reed frequency meter is shown in figure 17-14.

The current whose frequency is to be measured flows through the coil and exerts maximum


COIL
SOFT-IRON ARMATURE
REED
BAR
FLEXIBLE SUPPORT
CURRENT WHOSE FREQUENCY IS TO BE MEASURED
55 CYCLES
60 CYCLES
65 CYCLES
REEDS
BAR

(A) CIRCUIT

(B) REEDS


55
56
57
58
59
60
61
62
63
64
65
CYCLES PER SECOND
VIBRATING REED

(C) INDICATOR DIAL

Figure 17-14.—Simplified diagram of a vibrating-reed frequency meter.

attraction on the soft-iron armature TWICE during each cycle (fig. 17-14 (A)). The armature is attached to the bar, which is mounted on a flexible support. Reeds of suitable dimensions to have natural vibration frequencies of 110, 112, 114, and so forth, up to 130 cycles per second are mounted on the bar (fig. 17-14 (B)). The reed having a frequency of 110 cycles is marked "55" cycles, the one having a frequency of 112 cycles is marked "56" cycles, the one having a frequency of 120 cycles is marked "60" cycles, and so forth.

When the coil is energized with a current having a frequency between 55 and 65 cycles, all the reeds are vibrated slightly; but the reed having a natural frequency closest to that of the energizing current (whose frequency is to be measured) vibrates through a larger amplitude. The frequency is read from the scale value opposite the reed having the greatest amplitude of vibration.

In some instruments the reeds are the same lengths, but are weighted by different amounts at the top so that they will have different natural rates of vibration.

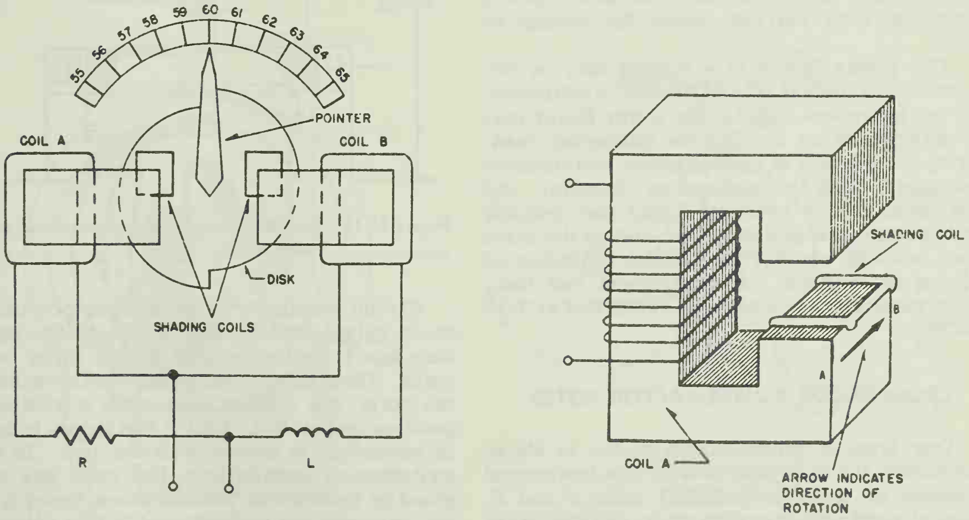
An end view of the reeds is shown in the indicator dial of figure 17-14 (C). If the energizing current has a frequency of 60 cycles per second, the reed marked ''60'' cycles will vibrate the greatest amount, as shown.

MOVING-DISK FREQUENCY METER

A moving-disk frequency meter is shown in figure 17-15 (A). Each of the two-pole fields (fig. 17-15 (B)) has a short-circuited turn (shading coil) on one side of the pole face and a magnetizing coil around the associated magnetic circuit. As in a shaded-pole motor, the magnetic field tends to produce rotation toward the shorted turn (*A* to *B*). One coil tends to turn the disk clockwise, and the other, counterclockwise. Magnetizing coil *A* is connected in series with a large value of resistance. Coil *B* is connected in series with a large inductance and the two circuits are supplied in parallel by the source.

For a given voltage, the current through coil *A* is practically constant. However, the current through coil *B* varies inversely with the frequency. At a higher frequency the inductive reactance is greater and the current through coil *B* is less; the reverse is true at a lower frequency. The disk turns in the direction determined by the stronger coil.

A perfectly circular disk would tend to turn continuously. This is not desirable, and accordingly the disk is constructed so that it will turn only a certain amount clockwise or counterclockwise about the center position, which is commonly marked ''60'' cycles on commercial equipment. To prevent the disk from turning more than the desired amount, the left half of the disk is mounted so that when motion occurs, the same amount of disk area will always be between the poles of coil *A*. Therefore, the force produced by coil *A* to rotate the disk is constant for a constant applied voltage. The right half of the disk is offset, as shown in the figure. When the disk rotates clockwise, an increasing area will come between the poles of coil *B*; when it rotates counterclockwise, a decreasing area will come between the poles of coil *B*. The greater



CIRCUIT
(A)

COIL
(B)

Figure 17-15.—Simplified diagram of a moving-disk frequency meter.

the area between the poles, the greater will be the disk current and the force tending to turn the disk.

If the frequency applied to the frequency meter should decrease, the reactance offered by *L* would decrease and the field produced by coil *B* would increase; the field produced by coil *A* would remain the same. Thus, the torque produced by coil *B* would tend to move the disk and the pointer counterclockwise until the area between the poles was reduced sufficiently to make the two torques equal. The scale is calibrated to indicate the correct frequency.

If the frequency should increase, the reactance offered by *L* would increase and the field produced by coil *B* would decrease; the field produced by coil *A* would remain the same. Thus, the decreasing torque produced by coil *B* would permit a greater disk area to move under the coil, and therefore the disk and the pointer would move clockwise until the two torques were balanced.

If the frequency is constant and the voltage is changed, the currents in the two coils—and therefore the opposing torques—change by the same amount. Therefore, the indication of the instrument is not affected by a change in voltage.

Single-Phase Power-Factor Meter

The power factor of a circuit is the ratio of the true power to apparent power. It is also equal to the cosine of the phase angle between the circuit current and voltage. A pure resistance has a power factor of unity (the current and voltage are in phase and the true power and the apparent power are the same); a pure inductance has a power factor of zero (current lags the voltage by 90°); and a pure capacitance has a power factor of zero (current leads the voltage by 90°).

The power factor of a circuit may be determined by the use of a wattmeter, a voltmeter, and an ammeter—that is, the power factor may be determined by dividing the wattmeter reading by the product of the voltmeter and ammeter readings. This is inconvenient, however, and instruments have been developed that indicate continuously the power factor and at the same time indicate whether the current is leading or lagging the voltage. An instrument that indicates these values is called a POWER-FACTOR METER.

CROSSED-COIL POWER-FACTOR METER

One type of power-factor meter is shown schematically in figure 17-16. The instrument consists of movable potential coils *A* and *B*, fixed at right angles to each other, and stationary current coil *C*. Coils *A* and *B* are pivoted, and the assembly, together with the attached pointer, is free to move through an angle of approximately 90°. Coil *A* is in series with inductor L, and the combination is connected across the line. Coil *B* is in series with noninductive resistor *R*, and the combination is also connected across the line.

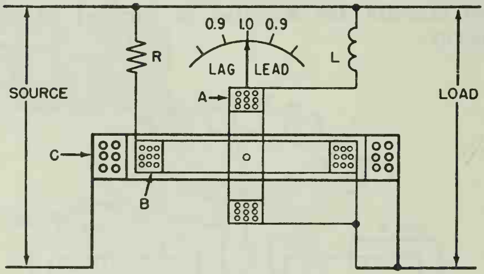


Figure 17-16.—Simplified diagram of a crossed-coil power-factor meter.

Circuit continuity to the coils is provided by three spiral springs (not shown in the figure) that exert negligible restraining force on the coils. Therefore, when no current flows through the coils, the pointer may come to rest at any position on the dial. Coil *C* (not drawn to scale) is connected in series with the line. In many switchboard installations the coils are energized by instrument transformers, in which case the currents are proportional to line values but not equal to them.

The current in coil *B* is in phase with the line voltage. The current in coil *A* lags the line voltage by 90°. When the line current is in phase with the line voltage, the currents in *B* and *C* are in phase and a torque is exerted between them that alines their axes so that the pointer indicates unity power factor. The average torque between *A* and *C* is zero because these currents are 90° out of phase when the line power factor is unity.

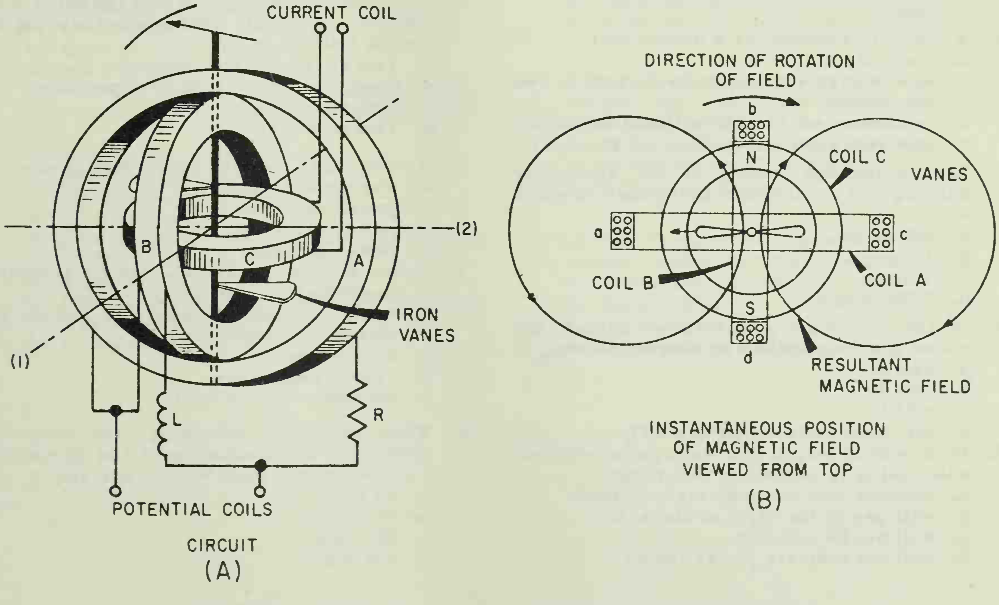
When the current in coil *C* lags the line voltage—for example, by 45°—the currents in coil *A* and coil *B* both will be out of phase with the current in *C*. The current in *A* lags the current in *C* by 45° and the current in *B* leads the current in *C* by 45°. The flux around coil *C* will therefore react with the resultant of the fluxes around coils *A* and *B*, which is in phase with the current of *C*, and the pointer will be moved to an intermediate position (45°) between zero power factor and unity power factor. In most power-factor meters, lagging current causes the pointer to move to the left of the central position (marked "1" on the scale) and a leading current causes the pointer to move to the right of the central position.

MOVING IRON-VANE POWER-FACTOR METER

A diagram of a moving iron-vane type of power-factor meter is shown in figure 17-17. In part (A) of the figure, potential coil *A* in series with resistor *R* comprises a resistive circuit, which is connected across the line. Potential coil *B* in series with inductor *L* comprises an inductive circuit, which is also connected across the line. Current coil *C*, having a few turns of large wire, is connected in series with the line. All coils are fixed in the positions shown, and only the iron vanes are free to move. The current in *B* lags the line voltage by 90°. The current in *A* is in phase with the line voltage. Hence, the current in *B* lags the current in *A* by 90° and, since the axes of *A* and *B* are displaced 90°, a magnetic revolving field is established by these coils when they are energized. The iron vanes are free to rotate about the axis of coil *C*. These vanes are magnetized alternately north and south by the line current flowing in coil *C*.

None of the moving parts carry current, and therefore springs are not needed. The movement is free to rotate 360°, but is prevented from rotating with the rotating field by an aluminum disk that rotates in a field produced by drag magnets (disk and magnets not shown).

In figure 17-17 (B), a two-pole rotating field is assumed to revolve at synchronous speed in



POTENTIAL COILS CIRCUIT
(A)

INSTANTANEOUS POSITION OF MAGNETIC FIELD VIEWED FROM TOP
(B)

Figure 17-17.—Simplified circuit of a moving iron-vane power-factor meter.

a clockwise direction. The vanes are attracted or repelled by this field depending on the instantaneous direction of the resultant flux produced by *A* and *B* and on the instantaneous polarity of the iron vanes as determined by the instantaneous direction of the current through *C*. The vanes will assume a position out of alinement with the field (position of minimum torque) when the line power factor is unity.

If, at the instant shown in figure 17-17 (B), the current in coil *C* is maximum and the resultant flux produced by coils *A* and *B* passes through the movable element at right angles to the vanes (and has no effect on them), the pointer will indicate unity power factor, as shown. Ninety degrees later, the resultant north-south field will pass through the iron vanes in alinement with them. At this instant the current in magnetizing coil *C* is zero and the torque on the vanes is again a minimum. If the current through *C* leads the line voltage by 45° (line power factor 70% leading), the vanes will move 45° to a new position of minimum torque. The current in *C* will become maximum earlier in the cycle and the revolving field will occupy a new position, again out of alinement with the vanes at this instant.

If the line current lags the line voltage, the pointer will come to rest on the opposite side of the unity power-factor mark.

QUIZ

1. A wattmeter is connected in a circuit with the current coil
   a. and the potential coil in parallel with the load
   b. in parallel and the potential coil in series with the load
   c. in series and the potential coil in parallel with the load
   d. and the potential coil in series with the load
2. A metallic rectifier is a device that
   a. converts d.c. to a.c.
   b. offers high opposition to current in two directions
   c. is classed as a unidirectional conductor
   d. has two good conductors of electricity
3. The amperage rating of the secondary windings of a current transformer is rated at
   a. 400 amps.
   b. 12 amps.
   c. 5 amps.
   d. 2,000 amps.
4. In the iron-vane power factor meter, the vanes are magnetized by current flowing in
   a. coil A
   b. coil B
   c. coil C
   d. all three coils simultaneously
5. In a wattmeter, if the voltage or current safe rating is exceeded, the meter
   a. reading may not indicate overload
   b. will peg to the right of the scale
   c. will not be affected
   d. will not indicate power factor
6. The path for current flow through a rectifier cell is
   a. from the conductor, across the barrier layer, through the semiconductor
   b. from the semiconductor, across the barrier layer, through the conductor
   c. in the direction of the arrow
   d. through the fin assembly
7. In a capacitor bridge, to find the value of an unknown capacitor, what is used to bring the circuit into balance?
   a. Two variable capacitors
   b. Capacitive reactance of capacitors
   c. Two resistors
   d. Two potentiometers
8. A watt-hour meter reads the product of
   a. energy and time
   b. power and current
   c. power and time
   d. power and energy
9. Under normal conditions, the fin assembly in a rectifier is used to
   a. apply uniform pressure to reduce internal resistance
   b. carry current
   c. create resistance
   d. dissipate excess heat
10. When using the vibrating-reed frequency meter, if the frequency of the current is 112 cycles, the reed will be marked
    a. 55 c.p.s.
    b. 56 c.p.s.
    c. 60 c.p.s.
    d. 112 c.p.s.

11. In the iron-vane power factor meter, the spiral springs
    a. are eliminated
    b. return the pointer to zero
    c. oppose torque
    d. carry current to coils A and B
12. Instruments for measuring high voltage circuits become inaccurate when connected directly to high voltage because of
    a. electrostatic forces acting on the transformer
    b. inexpensiveness of instrument indicators
    c. high hysteresis effect on indicating element
    d. electrostatic forces acting on indicating element
13. The normal efficiency of a copper-oxide rectifier is from
    a. 25% to 55%
    b. 55% to 65%
    c. 85% to 100%
    d. 65% to 85%
14. In the moving-disk frequency meter, the magnetic field tends to produce rotation toward
    a. coil A
    b. the magnetizing coil
    c. the shorted coil
    d. coil B
15. When reading a watt-hour meter, the dials are read
    a. from the next highest number that the needle has just passed
    b. left to right
    c. right to left
    d. and subtracted
16. Instruments that are used to measure voltage and current regardless of circuit ratings are
    a. instrument transformers
    b. autotransformers
    c. electrodynamometers
    d. D'Arsonvals
17. A D'Arsonval d-c type instrument can be converted to read a. c. by using
    a. a bridge rectifier unit
    b. four rectifier cells connected in series
    c. a selenium rectifier
    d. a copper-oxide rectifier
18. In the moving-disk frequency meter, the current through coil B (fig. 17-15) varies
    a. inversely with the frequency
    b. directly with the frequency
    c. because it is connected in parallel
    d. because inductive reactance is constant
19. A safety precaution to follow when using a potential transformer is to
    a. ground the secondary
    b. ground the primary
    c. insulate for high current
    d. connect it in series with the line
20. The primary of a current transformer is always connected in
    a. series with the primary
    b. series with the line
    c. parallel with the line
    d. parallel with the power source.
21. The wattmeter is a/ an
    a. D'Arsonval meter
    b. electrodynamometer
    c. potential coil meter
    d. iron-vane meter
22. A power factor meter measures the
    a. phase angle between current and voltage
    b. sine of the phase angle between current and voltage
    c. ratio of apparent power to true power
    d. ratio of true power to apparent power
23. The secondary of a current transformer should not be open-circuited because
    a. of high current in the primary
    b. of high voltage in the secondary
    c. of low current in the primary
    d. it is not grounded
24. In the crossed-coil power factor meter, circuit continuity to the coils is provided by
    a. stationary current coil
    b. the resistor
    c. the inductor
    d. three spiral springs

CHAPTER 18

MAGNETIC AMPLIFIERS

Amplification of voltage and power can be accomplished by means of the magnetic amplifier, which employs as its controllable element an iron-core saturable reactor. The magnitude of the impedance of the saturable reactor depends upon the range of flux change that occurs in its core, and this action, in turn depends upon the magnitude of the control current. If the control current is varied a small amount, the power delivered to a load is varied through a much wider range. Herein lies the action of amplification.

The magnetic amplifier has certain advantages over other types of amplifiers. These include (1) high efficiency (90 percent); (2) reliability (long life, freedom from maintenance, reduction of spare parts inventory); (3) ruggedness (shock and vibration resistance, overload capability, freedom from effects of moisture); and (4) no warmup time. The magnetic amplifier has no moving parts and can be hermetically sealed within a case similar to the conventional dry-type transformer.

Also, the magnetic amplifier has a few disadvantages. For example, it cannot handle low-level signals; it is not useful at high frequencies; it has a time delay associated with magnetic effects; and the output waveform is not an exact reproduction of the input waveform.

The magnetic amplifier is important, however, to many phases of naval engineering because it provides a rugged, trouble-free device that has many applications aboard ship and in aircraft. These applications include throttle controls on the main engines of ships, speed, frequency, voltage, current, and temperature controls on auxiliary equipment; fire control, servomechanisms, and stabilizers for guns, radar, and sonar equipment.

Early Types of Saturable Cores

Early saturable reactors employed ordinary transformer silicon-steel cores. The amplifying qualities of these devices were not very satisfactory because of the relatively low-saturation flux density and high hysteresis losses.

The evolution of a practical magnetic amplifier has resulted from the recent development of high quality steels, gapless construction of the magnetic circuit, special low-leakage rectifiers, and self-saturating magnetic circuits. The improvement in processing magnetic materials and the successful development of dry-disk or metallic rectifiers have contributed principally to the wide use of this device as an amplifier. High-quality steels have increased the power-handling capacity. The dry-disk rectifiers convert either the entire output or part of the output from alternating current to direct current.

Basic Principles of Operation

To introduce the concept of controlling the magnitude of the current through a load by means of the self-induced voltage in a reactor (fig. 18-1), apply a 60-cycle, 117-volt source having a sine-waveform across a series circuit containing a variable inductance (the controlled element) and a fixed resistor (the load). The d-c control voltage is discussed later.

The circuit (fig. 18-1 (A)), although not an accurate analogy of magnetic amplifier action, represents the control of the magnitude of load

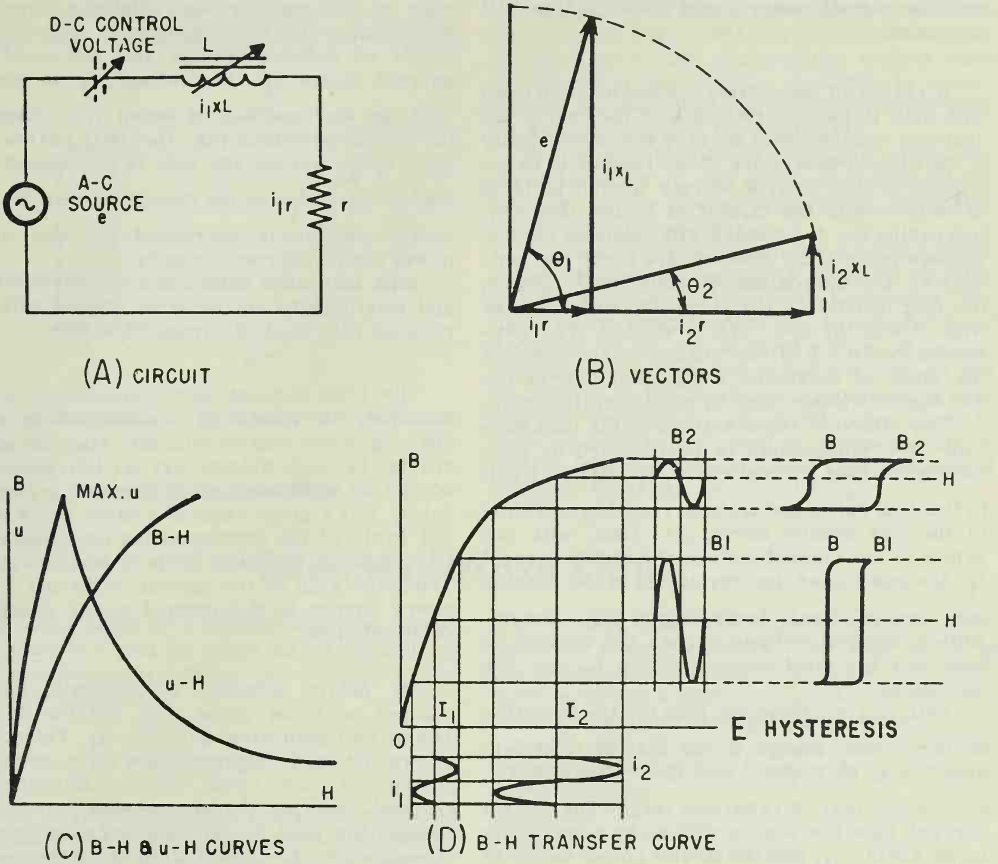

D-C CONTROL
VOLTAGE
L
i_1
$i_1 x_L$
A-C
SOURCE
e
$i_1 r$
r
(A) CIRCUIT
e
$i_1 x_L$
θ_1
θ_2
$i_2 x_L$
$i_1 r$
$i_2 r$
(B) VECTORS
B
u
MAX. u
B-H
u-H
H
(C) B-H & u-H CURVES
B
B2
B
B2
H
B1
B
B1
H
I_1
I_2
O
i_1
i_2
E HYSTERESIS
(D) B-H TRANSFER CURVE

Figure 18-1.—Load current controlled by variable inductance.

current by utilizing the induced voltage inherent in the reactor, *L*.

Lenz's law states that the induced e.m.f. in any circuit is always in such a direction as to oppose the effect that produces it. Because the current in an a-c circuit is always changing, the opposition of the induced voltage is continuous. Increasing the induced voltage in the series circuit comprising *r* and *L* will reduce the magnitude of the circuit current and cause it to lag behind the source voltage by an increasing angle (fig. 18-1 (B)). This action reduces the circuit power factor.

The obvious advantage of controlling the circuit current with adjustable inductance is the absence of appreciable heat loss in the control element. The obvious disadvantage is low circuit power factor.

Magnitude of the inductance may be varied in a number of ways. For example, doubling the number of turns will quadruple the inductance. (Inductance varies as the square of the number of turns.) Also increasing the permeability of the core will increase the inductance. (Inductance varies directly with permeability.)

The latter action may be accomplished in a number of ways. For example, if the reactor core is air, the permeability, μ, will be unity. If a laminated silicon-steel core is gradually inserted into the coil, the permeability will increase (fig. 18-1 (C)) toward the point of maximum μ. The coil impedance will increase and the circuit current and power factor will decrease.

A review of magnetism and magnetic circuits will help in the understanding of the rest of the chapter. Another way to vary the permeability of the silicon-steel core of the reactor is to introduce a d-c control voltage (dotted battery) in series with the circuit of figure 18-1 (A). Increasing the d-c voltage will increase the d-c ampere turns and H (the ampere turns per centimeter are approximately equal to H). Hence, the flux density, B (fig. 18-1 (D)) will increase with H and the d-c control voltage. The permeability ($\mu = B/H$) decreases to the right of the point of maximum, μ (fig. 18-1 (C)) as the d-c control voltage (and H) continue to increase.

The effect of these actions on the load current (a-c component) is represented by projecting the load current curve, i_1 (fig. 18-1 (D)) to the B-H curve and transferring the projection to the flux density curve, $B1$. Thus, with low values of d-c control voltage and direct current I_1, the associated flux variations in the reactor core are relatively large (curve $B1$). The resulting induced voltage across the reactor is high and the load current, curve i_1, has low amplitude.

Voltage $i_1 r$ across the load for the condition of large flux change in the coil is relatively small (fig. 18-1 (B)), and the voltage, $i_1 X_L$, across the coil is relatively large. The circuit current lags the source voltage by a relatively large angle, 0_1, and the circuit power factor is low.

Increasing the d-c control voltage and direct current from I_1 to I_2 will partially saturate the core so that smaller flux variations (curve B2) will occur with a correspondingly reduced magnitude of induced voltage and increased load current (curve i_2). The voltage, $i_2 r$ across the load for the condition of small flux change in the coil is increased (fig. 18-1 (B)), and the voltage, $i_2 X_L$, across the coil is decreased. The angle, θ_2, by which the circuit current lags the source voltage is decreased, and the circuit power factor approaches unity.

With increased values of d-c control voltage and flux density the cycle of magnetization is reduced (fig. 18-1 (E)) from $B1$ to $B2$.

The load current (a-c component) in this example, is relatively insensitive to small changes in d-c control current. Also, the series reactor is never driven very far into saturation so that its impedance never drops to a very low value. For a given value of control current, the full cycle of the corresponding hysteresis loop is completed for each cycle of source voltage. Thus, the gain of the circuit (ratio of a-c load power change to d-c control power change) is relatively low.

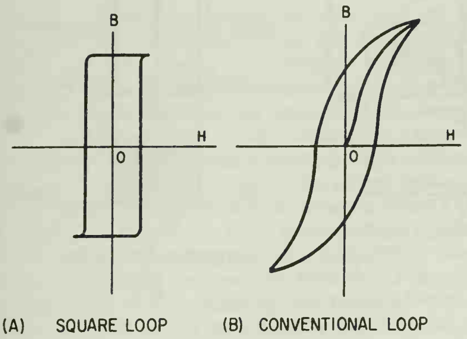
To obtain greater circuit gain, certain changes must be made. The reactor core is driven into saturation periodically. This action allows the load current to flow for a controlled portion of each cycle. Before saturation is reached, the flux change prevents current flow through the load for another controlled portion of each cycle. The result of operating the reactor core in the region of saturation for a portion of each cycle will increase the circuit gain materially.

Materials Suitable For Magnetic - Amplifier Cores

Various types of nickel-iron alloys that have more suitable magnetic properties than previous ones for use as core materials for saturable reactors have been developed and are commercially available. These materials are the (1) high permeability alloys and (2) grain-oriented alloys.

High-permeability materials, such as Permalloy A, Mumetal, 1040 alloy and equivalents have low and intermediate values of saturation flux density but relatively narrow and steep hysteresis loops. These materials are used extensively as the cores in low-level input amplifier stages.

Grain-oriented materials, such as Orthonol, Deltamax, Hypernik V, Orthonik, Permeron, and equivalents, have higher values of saturation flux density and more rectangular-shaped hysteresis loops (fig. 18-2 (A)) than the high-permeability materials. Grain-oriented materials are referred to as square-loop materials because of the flat top and bottom of the hysteresis loop. A conventional loop is shown in figure 18-2 (B). These materials are used as the cores in high-level output amplifier stages in which maximum permeability occurs close to saturation flux density, resulting in a substantial increase in the power-handling capacity for a given weight of core material.



(A) SQUARE LOOP (B) CONVENTIONAL LOOP

Figure 18-2.—Hysteresis loops.

In the manufacture of saturable cores, the characteristics of the grain structure of the material can be altered considerably by rolling and annealing processes.

A great improvement in the magnetic properties of some materials is obtained by cold-rolling the material before it is annealed. The cold-rolling process develops an orientation of the grain in the direction of rolling. If a magnetizing force is applied to the material so that the flux is in the direction of the grain, a rectangular hysteresis loop is obtained. Thus, in some materials cold rolling produces almost infinite permeability up to the knee and almost complete saturation beyond the knee.

Basic Half-Wave Circuit

A description of a simple half-wave circuit (fig. 18-3 (A)) will be given as an example of the operating principles in general of the magnetic amplifier.

WINDINGS

The magnetic amplifier contains a magnetic core made of a square-loop material upon which two windings are placed. The load, or ''gating'' winding, *L*, is connected in series with a rectifier, the load, and an a-c power supply. A second or ''control'' winding, *C*, is connected in series with a rectifier, the control signal source, and the same a-c source. The two windings have a 1:1 turns ratio. The magnetic amplifier acts in this circuit like an electrically operated contactor that gates (turns on) the load circuit periodically. A control voltage applied to the closing circuit of the contactor closes the contactor, which completes a circuit to the load. This action can be repeated periodically, for example, by introducing an a-c control voltage in series with a half-wave rectifier and the contactor closing coil.

The action of the control winding of the magnetic amplifier may be compared to that of the closing coil of the contactor. The action of the load winding may be compared to that of the contactor's main contacts. The latter action is that of introducing a high impedance (main contacts open) for a controlled portion of each half cycle and then removing this impedance (main contacts closed) and allowing current to flow through the load during the remaining portion of the half cycle.

POLARITIES

In a previous study it was explained that transformers have polarity markings (fig. 18-4). The solid arrow at the source is marked minus at the head and plus at the tail to represent arbitrarily the positive half cycle of active source voltage. The electron flow is from the negative terminal of the source into the dotted end of the primary and returning to the positive end of the source.

The solid arrow in the secondary of the transformer has the same polarity as that of the source because the secondary is the source for the load.

The dotted (dashed line) arrow in the primary winding represents the induced voltage in the primary for the first half cycle of applied voltage and has the same polarity markings as

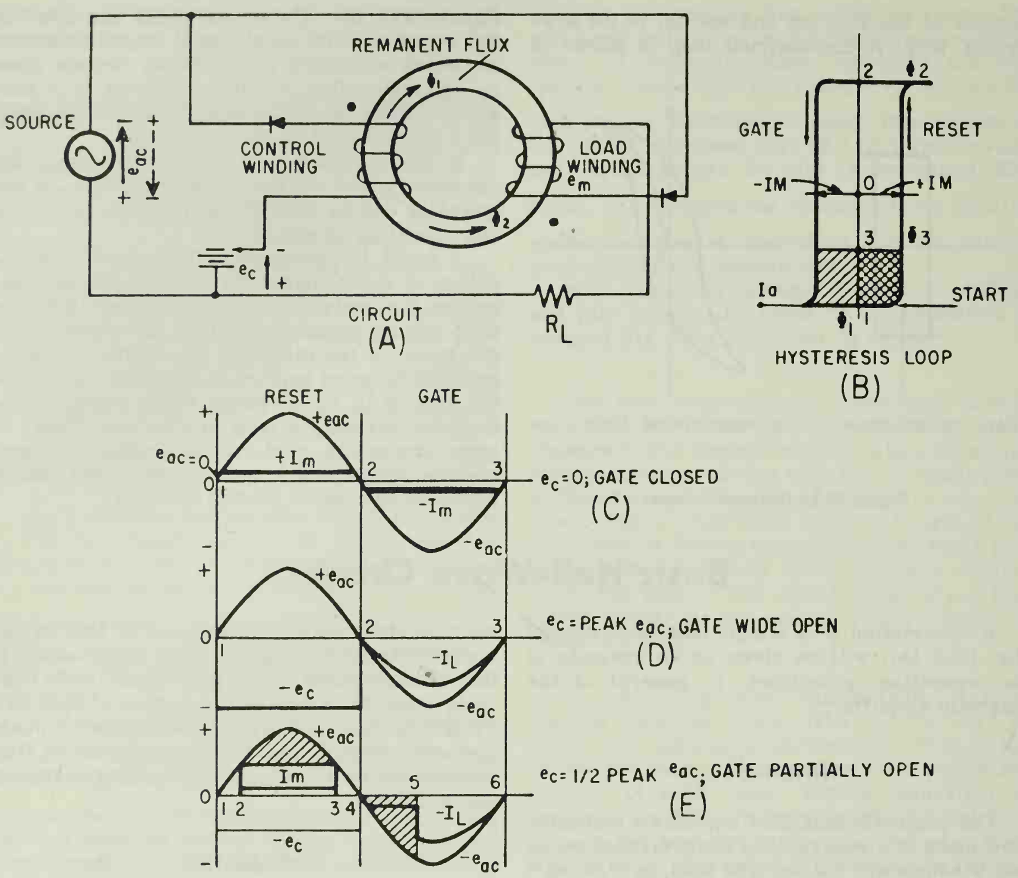

REMANENT FLUX
SOURCE
e_{ac}
CONTROL WINDING
LOAD WINDING
e_m
ϕ_1
ϕ_2
e_c
CIRCUIT
(A)
R_L
GATE
RESET
-IM
+IM
0
2
3
ϕ_2
ϕ_3
Ia
START
ϕ_1
1
HYSTERESIS LOOP
(B)
RESET
GATE
$+e_{ac}$
$e_{ac}=0$
$+I_m$
$-I_m$
$-e_{ac}$
$e_c=0$; GATE CLOSED
(C)
$-I_L$
$-e_c$
$e_c=$ PEAK e_{ac}; GATE WIDE OPEN
(D)
Im
1 2 3 4 5 6
$e_c=1/2$ PEAK e_{ac}; GATE PARTIALLY OPEN
(E)

Figure 18-3.—Basic half-wave magnetic amplifier.

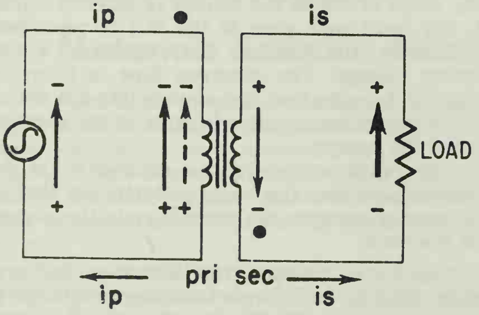

ip
is
LOAD
pri
sec
ip
is

Figure 18-4.—One-half cycle of applied voltage e_{ac}.

the source voltage and the secondary voltage arrows.

The direction of electron flow through the load is represented by a solid arrow, the polarity of which is opposite to that of the other three arrows. This reversal of markings is characteristic of load voltages with respect to source voltages. For voltages across loads, the arrow head is on the positive side and the tail is on the negative side. For voltages originating in generators, transformers, batteries, etc., the arrow head is on the negative side and the tail is on the positive side.

In the example of figure 18-3 (A), the solid arrow at the source indicates the direction of electron flow through the circuit during the positive half cycles of applied voltage, e_{ac}. The polarity markings (dots at one end of the windings) are indicative of the way the turns are wound on the core. The dotted ends of the windings of a core are assumed to always have a particular instantaneous polarity with respect to the undotted ends of the windings. Also, the dotted ends of two or more windings on a common core are considered to have the same instantaneous polarity with respect to each other. For example, in figure 18-3 (A), if the voltage applied to the control winding is of a polarity at some instant to cause current to flow INTO the dot-marked end of that winding, the induced voltage of the other winding will be of a polarity (at the same instant) such as to cause current to flow OUT of the dot-marked end of that winding. The control voltage, e_c, is assumed to be a direct voltage. The rectifier arrow-heads are pointed against the direction of electron flow.

FUNCTION OF RECTIFIERS

Rectifiers are placed in the load and control circuits to prohibit current flow in the control circuit during the gating half cycle and in the load, or gating, circuit during the reset half cycle. The magnetic amplifier is not an amplifier in the sense of a step-up transformer. Voltages generated by mutual induction (transformer action) between the control and load windings exist in these windings, but they have only a small effect on the amplifier operation under the established conditions.

During the first half cycle (solid arrow of source) of the applied voltage, the direction of the INDUCED voltages in both windings is INTO, or positive, at the polarity-marked terminals. In the load winding this action is in the forward direction of the rectifier and against e_{ac}. Thus, the rectifier in the load circuit prevents current flow through the load and is subjected to an inverse voltage equal to the difference between e_{ac} and the mutually induced voltage in the load winding. The time interval, corresponding to the first half cycle, is called the ''reset'' half cycle. The reset action is described later.

ANALYSIS WITH ZERO D-C CONTROL VOLTAGE

As mentioned previously, figure 18-3 is used in the analysis of the action of the basic half-wave magnetic amplifier. Figure 18-3 (A), represents the basic circuit. Figure 18-3 (B) represents the square-type hysteresis loop for the core material used in this circuit. Figure 18-3 (C), (D), and (E), represents the waveforms of current and voltage for three conditions to be considered. The symbol representing a quantity is common to all parts of the figure. For example, the magnetizing current, I_m, is represented in figure 18-3 (B), (C), and (E). The hysteresis loop is enlarged for clarity and is not drawn to the same scale as parts (C), (D), and (E).

Reset Half Cycle

The first condition to be described is with the control voltage, e_c, at zero. At the beginning of the reset half cycle, the core is assumed to possess a residual or negative saturation remanent flux level, Φ_1 (fig. 18-3 (B)). The direction of this flux is indicated by the arrow, Φ_1, in figure 18-3 (A). As e_{ac} increases from 0 in a positive direction (indicated by the solid arrow at the source, fig. 18-3 (A) and by the part of the sine curve, point 1 to point 2 (fig. 18-3 (C)), the current in the control winding establishes an m.m.f. represented by half the width of the hysteresis loop, $+I_m$ (fig. 18-3(B)). The applied voltage establishes an m.m.f. that acts in a direction to oppose the residual core flux, Φ_1, and therefore to demagnetize the core. The amount of change of flux will depend upon the MAGNITUDE of the applied voltage across the control winding and the TIME INTERVAL during which this voltage is applied.

In this example, the first half cycle of applied voltage is assumed to reverse the core magnetism and to establish its flux density at essentially the positive saturation level, Φ_2 (fig. 18-3 (B)). This action is called reset.

As e_{ac} increases from 0 in a positive direction in the vicinity of point 1 (fig. 18-3 (C)), there is no change in core flux until the current increases to the value of $+I_m$, corresponding to one-half of the width of the hysteresis loop. Thus, with no flux change, the current rises abruptly and is limited only by the resistance of the circuit and the low value of e_{ac}. When the current reaches the value, $+I_m$, the core flux starts to change from the Φ_1 level toward the Φ_2 level (fig. 18-3 (B)). The accompanying self-induced voltage opposes e_{ac} and limits the current to a constant small value during the flux variation from the level Φ_1 to Φ_2.

This flux change continues during the time interval between point 1 and point 2 (fig. 18-3 (C)). As it continues, the induced voltage continues to vary in magnitude with e_{ac} and to oppose e_{ac} in such a manner that I_m remains constant over the half-cycle interval.

Gating Half Cycle

The next half cycle is called the "gating" half cycle. It starts at point 2 (fig. 18-3 (C)), at which time the polarity of the applied voltage reverses. The direction of e_{ac} for this half cycle is indicated by the dotted arrow (fig. 18-3 (A)). During this time interval, the rectifier in the control circuit blocks the flow of control circuit current. However, the rectifier in the load circuit permits current from the source to flow in that circuit. This current will magnetize the core in a negative direction—that is, in a direction to change the flux from the Φ_2 level to the Φ_1 level. The applied voltage is assumed to be of the correct magnitude to cause the core to be magnetized to the Φ_1 level (fig. 18-3 (B)). A condition of equilibrium is indicated.

The large flux change from the Φ_2 level to the Φ_1 level causes a self-induced voltage in the load winding, *L*, and a mutually induced voltage in the control winding, *C*. The self-induced voltage in the load winding opposes e_{ac}. The mutually induced voltage in the control winding also opposes e_{ac}. The rectifier in the control circuit is subject to an inverse voltage equal to the difference between e_{ac} and the mutually induced voltage in the control winding. Because of the maximum flux change in the core, maximum impedance is presented by the load winding to the circuit containing R_L throughout the gating half cycle, and therefore e_{ac} will appear across the load winding and not across R_L. For this condition, the current through the load is limited to a very small magnetizing component that is negligible compared to normal values of load current. The gate is closed.

ANALYSIS WITH MAXIMUM D-C CONTROL VOLTAGE

The second condition described is for the condition that e_c is equal to the peak value of e_{ac}. At point 1 (fig. 18-3 (D)) the remanent magnetism is again at the Φ_1 level (fig. 18-3 (B)).

First Half Cycle

The applied voltage, e_{ac}, rises from 0 to maximum during the first 90° of the cycle, but has no effect on the core flux because the control voltage, e_c, has a magnitude equal to the maximum value of e_{ac}, and the polarity opposite to that of e_{ac}. Thus, the rectifier prevents the flow of battery control current during the time that e_c is greater than e_{ac}. Because there is no voltage across the control winding (the rectifier is essentially an open circuit), no flux change can occur from point 1 to point 2 (fig. 18-3 (D)). Figure 18-3 (B), does not apply. Thus, no change in flux occurs during the reset half cycle for this assumed condition.

Second Half Cycle

When e_{ac} reverses its polarity (solid to dotted arrow), the rectifier in the control circuit continues to block the flow of current in that circuit. In the load circuit the polarity of e_{ac} during the gating interval, points 2 to 3 (fig. 18-3 (D)), is such as to tend to drive the core further into negative saturation (point Ia, fig. 18-3 (B)). Because the core is already saturated, no further flux change occurs, and e_{ac} appears across R_L because the load winding offers no impedance to I_L.

The full value of load current flows, and its magnitude is e_{ac}/R_L. The gate is wide open. The waveform of this current, $-I_L$, is illustrated in figure 18-3 (D).

ANALYSIS WITH PARTIAL D-C CONTROL VOLTAGE

The third condition assumes that e_c is approximately half peak value of e_{ac}. During the reset half cycle, voltage is applied to the control winding during the time interval from point 2 to point 3 (fig. 18-3 (E)). The magnitude of this voltage is $e_{ac} - e_c$. This voltage will be less than the peak value of e_{ac}, but greater than zero; and a new set of conditions will be established.

First Half Cycle

The reset cycle is just beginning. During the interval 1 to 2 (fig. 18-3 (E)), e_c is greater than e_{ac}, and the rectifier opposes any current flow in the control winding. During the interval 2 to 3, e_{ac} exceeds e_c, and magnetizing current flows in the control winding. As mentioned previously, the extent of the change in core flux will depend on the time interval and magnitude of the voltage applied across the control winding within the half cycle. Because the time interval is very short, and the net voltage applied to the control winding is much less than e_{ac}, the core flux level is assumed to change from Φ_1 to the level along the line through Φ_3 (fig. 18-3 (B)). During the interval 3 to 4 (fig. 18-3 (E)), e_{ac} is again less than e_c, and the rectifier prevents any further flow of control current. As in the previous examples, the rectifier in the load circuit prevents any current flow in that circuit during the reset half cycle.

Second Half Cycle

When e_{ac} reverses, magnetizing current flowing through the load winding changes the core flux from the level through point 3 to the level through point 1 (fig. 18-3 (B)). This change is assumed to take place during the interval 4 to 5 (fig. 18-3 (E)). The impedance of the load winding is high during this interval, and current flow through the load is restricted to the magnetizing current. However, at point 5 the core becomes saturated, and no further flux change occurs. The impedance of the core drops to zero, and current e_{ac}/R_L flows through the load during the interval 5 to 6. The load voltage is in phase with e_{ac} and has the same waveform as that of e_{ac} for this part of the cycle.

ENERGY CONSIDERATIONS

The area of the portion of the hysteresis loop traversed is a measure of the energy required to complete that particular cycle of magnetization. It may be divided equally by the y axis.

For condition 1 (fig. 18-3 (C)), the entire right-hand area of the loop shown is figure 18-3 (B), is proportional to the area under the $+e_{ac}$ voltage wave (which is proportional to the energy supplied), and the left-hand area is proportional to the area under the $-e_{ac}$ voltage wave.

For condition 2 (fig. 18-3 (D)), the area in both half cycles is zero (no flux change occurs), and the load, R_L, absorbs the entire applied voltage, e_{ac}. No energy is supplied to the control winding.

For condition 3 (fig. 18-3 (E)), the right-hand shaded area of the hysteresis loop (fig. 18-3 (B)) is proportional to the shaded area under $+e_{ac}$ (fig. 18-3 (E)), and the left-hand shaded area of the hysteresis loop is proportional to the shaded area of $-e_{ac}$. In this case the magnitude of $(e_{ac} - e_c)$ applied to the control winding determines how far the core flux is carried from negative saturation toward positive saturation, and consequently, how much of the gating half cycle will be nonconducting.

For condition 3, the energy supplied to the control winding is partially reduced. The corresponding area is reduced from the total area under $+e_{ac}$ for condition 1 to that indicated by the shaded portion under the $+e_{ac}$ curve in figure 18-3 (E). The flux change is not carried to level Φ_2 on the hysteresis loop, but to some point part way up the loop (level Φ_3), as determined by the shaded area under the $+e_{ac}$ curve.

In other words, the time in the gating half cycle at which the core saturates (the firing angle) is determined by the shaded area under the $+e_{ac}$ curve or the amount of energy supplied to the control winding during the reset half cycle. Thus, as e_c is reduced in magnitude, the voltage, $e_{ac} - e_c$, applied to the control winding increases, and the core flux is carried further toward positive saturation during the reset half cycle.

This action increases the firing angle and delays the time in the gating half cycle when the core saturates and the load winding becomes conducting. Thus, the average load current and voltage are reduced. They both vary with the control voltage.

By way of contrast with the relative low-circuit power factor of the example in figure 18-1, the power factor of the circuit of the example in figure 18-3 is unity for all values of d-c control voltage between zero and maximum.

QUIZ

1. When control current is sufficient to saturate the core, inductance
    a. increases and reactance decreases
    b. decreases and reactance increases
    c. increases and reactance increases
    d. decreases and reactance decreases
2. The power handling capacity of magnetic amplifiers has been improved primarily because of the development of
    a. dry-disk rectifiers
    b. high-quality steels
    c. electron amplifier tubes
    d. high-wattage resistors
3. When the inductive reactance of the load winding is decreased load
    a. current rises and load voltage drops
    b. current drops and load voltage rises
    c. circuit impedance drops and load voltage rises
    d. circuit impedance drops and load voltage drops
4. Doubling the number of turns on a coil will
    a. double the inductance
    b. decrease the inductance by one-half
    c. increase the inductance as the square of the turns
    d. have no effect on inductance
5. Which of the following is a disadvantage of a magnetic amplifier?
    a. High efficiency
    b. Ruggedness
    c. It has no moving parts
    d. It is not useful at high frequencies
6. When a magnetic amplifier is operating at the knee of the magnetization curve, a small increase in control current will
    a. cause a large increase in flux density
    b. desaturate the core
    c. increase permeability of the core
    d. decrease inductance of the load winding
7. Transformer action between the a-c load windings and d-c control winding is
    a. necessary to increase amplification
    b. desired in order to reduce the required control current
    c. desired to increase response time
    d. not desired
8. Which of the following is considered an advantage of a magnetic-amplifier circuit over a vacuum-tube circuit?
    a. Little distortion
    b. Frequency response time
    c. Shock resistance
    d. Impedance matching
9. Current flow in the load circuit can be increased by
    a. increasing the impedance of the circuit
    b. decreasing the permeability of the core
    c. increasing the permeability of the core
    d. decreasing the control current
10. The basic control action of a magnetic amplifier depends upon
    a. variations in the load impedance
    b. changes in inductance
    c. type of core material
    d. construction of the core
11. Permeability of a substance is defined as the
    a. ease with which it conducts magnetic lines of flux
    b. opposition it offers to a-c current flow
    c. opposition if offers to d-c current flow
    d. ease with which it retains magnetic properties
12. Which of the following is an advantage of a magnetic amplifier?
    a. It has a time delay associated with magnetic effects
    b. The output waveform is not an exact reproduction of the input waveform
    c. No warmup time
    d. It cannot handle low-level signals

13. Rectifiers are placed in the control circuits to prohibit current flow in the control winding during the
    a. warmup time
    b. gating half cycle
    c. reset half cycle
    d. complete cycle
14. Silicon steel cores were not satisfactory for saturable reactors because of
    a. low saturation flux density and high hysteresis losses
    b. high saturation flux density and high hysteresis losses
    c. low saturation flux density and low hysteresis losses
    d. high saturation flux density and low hysteresis losses
15. An important advantage of controlling circuit current by an adjustable inductor is
    a. low circuit power factor
    b. high circuit power factor
    c. absence of heat loss in the control element
    d. high heat loss in the control element
16. Operating the reactor core in the region of saturation for a portion of each cycle will cause the circuit gain to
    a. hold steady
    b. fluctuate rapidly
    c. decrease
    d. increase

CHAPTER 19

SYNCHROS AND SERVOMECHANISMS

Synchros

Synchros, as identified by the Armed Forces, are electromagnetic devices which are used primarily for the transfer of angular-position data. Synchros are, in effect, single-phase transformers whose primary-to-secondary coupling may be varied by physically changing the relative orientation of these two windings.

Synchro systems are used throughout the Navy to provide a means of transmitting the position of a remotely located device to one or more indicators located away from the transmitting area.

Figure 19-1 (A) shows a simple synchro system. The synchro transmitter sends an electrical signal to the synchro receivers, via interconnecting leads. The synchro transmitter signal is generated when the handwheel turns the transmitter's shaft, and the indicator's shaft will rotate to aline with the transmitter's shaft.

Figure 19-1 (B) shows a simple mechanical system that uses gears and shafts for transmitting position data. Mechanical systems are usually impractical because of associated belts, pulleys, and flexible rotating shafts.

In appearance, synchros resemble small electric motors. They consist of a rotor (R) and a stator (S). The letters R and S are used to identify rotor and stator connections in wiring diagrams and blueprints. Synchros are represented schematically by the symbols shown in figure 19-2. The symbols shown in (A) and (B) are used when it is necessary to show only the external connections to a synchro, while those shown in (C), (D), and (E) are used when it is important to see the positional relationship between the rotor and stator. The small arrow on the rotor indicates the angular displacement of the rotor; in these illustrations the displacement is zero degrees.

SYNCHRO CONSTRUCTION

Knowledge of a synchro's construction and its characteristics will enable you to better understand synchro operation. As stated previously, synchros are, in effect, transformers whose primary-to-secondary coupling may be varied by physically changing the relative orientation of the two windings. This is accomplished by mounting one of the windings so that it is free to rotate inside the other. The inner, usually movable, winding is called the rotor, and the outer, usually stationary, winding is called the stator. The rotor consists of either one or three coils wound on sheet-steel laminations. The stator normally consists of three coils wound in internally slotted laminations. In some units the rotor is the primary and the stator is the secondary, in other units the reverse is true.

Rotor Construction

The laminations of the rotor core are stacked together and rigidly mounted on a shaft. Sliprings are mounted on, but insulated from, the shaft. The ends of the coil or coils are connected to these sliprings. Brushes riding on the sliprings provide continuous electrical contact during rotation, and low-friction ball bearings permit the shaft to turn easily. In standard synchros, the bearings must permit rotation from very low speeds to speeds as high as 1,200 r.p.m.

There are two common types of synchro rotors now in use, (1) the salient-pole rotor, and (2) the drum or wound rotor.

The salient-pole rotor, which frequently is called a "dumb-bell" or "H" rotor because of the shape of its core laminations, is shown in figure 19-3.

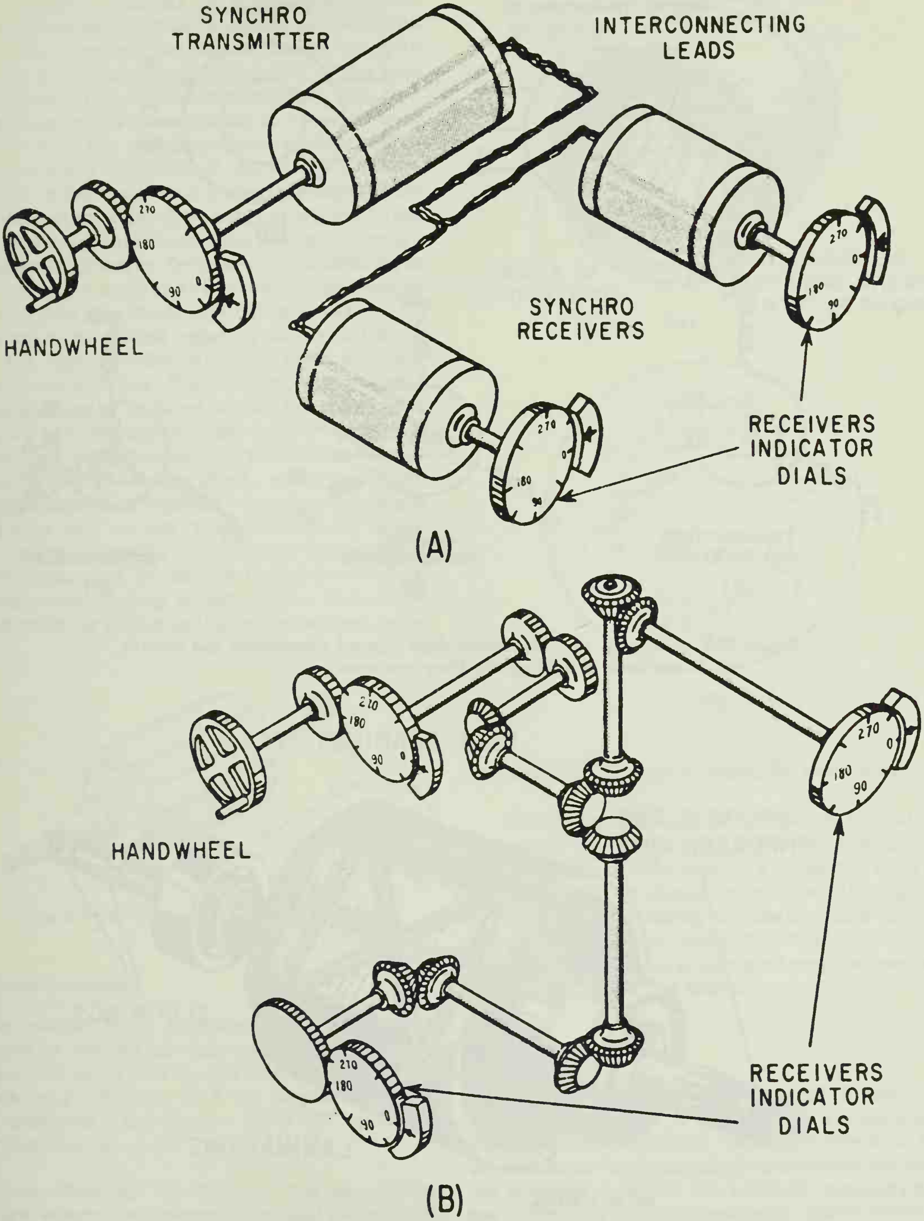

SYNCHRO TRANSMITTER
INTERCONNECTING LEADS
HANDWHEEL
SYNCHRO RECEIVERS
RECEIVERS INDICATOR DIALS
(A)
HANDWHEEL
RECEIVERS INDICATOR DIALS
(B)

Figure 19-1.—(A) Data transfer with synchros; (B) data transfer with gears.

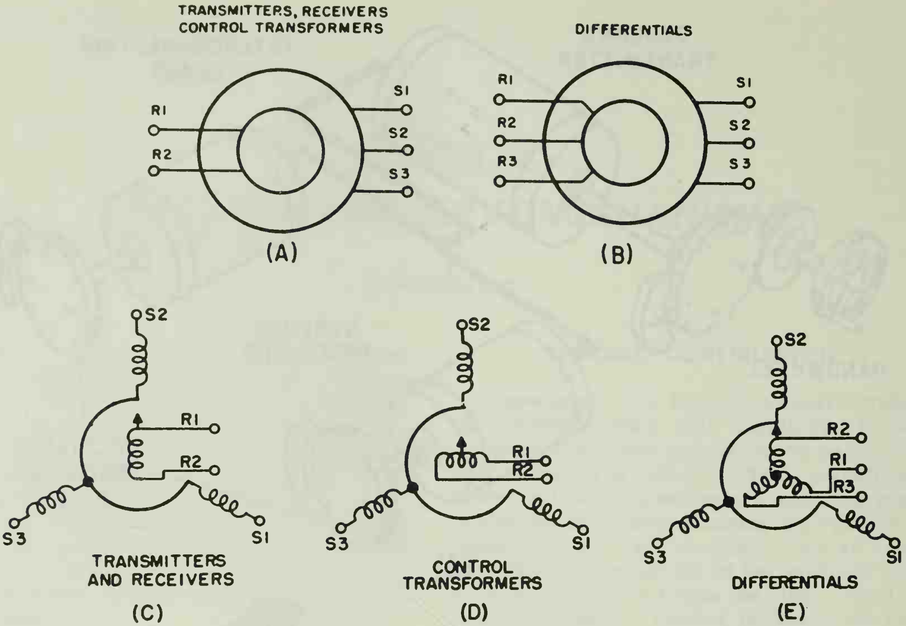

TRANSMITTERS, RECEIVERS
CONTROL TRANSFORMERS
R1
R2
S1
S2
S3
(A)
DIFFERENTIALS
R1
R2
R3
S1
S2
S3
(B)
S2
R1
R2
S3
S1
TRANSMITTERS AND RECEIVERS
(C)
S2
R1
R2
S3
S1
CONTROL TRANSFORMERS
(D)
S2
R2
R1
R3
S3
S1
DIFFERENTIALS
(E)

Figure 19-2.—Schematic symbols used to show external connections and relative positions of windings for Navy synchros.

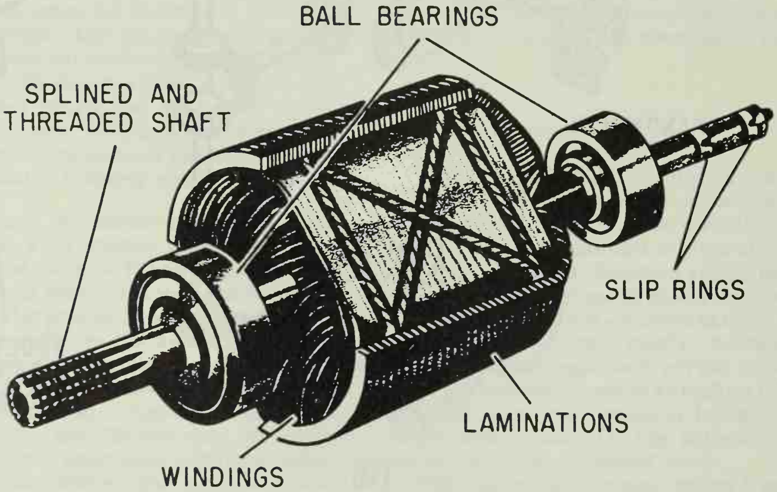

BALL BEARINGS
SPLINED AND THREADED SHAFT
SLIP RINGS
LAMINATIONS
WINDINGS

Figure 19-3.—Salient-pole rotor.

The winding consists of a single machine-wound coil whose turns lie in planes perpendicular to a line through the center called the axis of the coil and along which the m.m.f. of the coil is developed. The coil axis coincides with that of the salient poles. When used in transmitters and receivers, the rotor functions as the excitation or primary winding of the synchro. When energized, it becomes an a-c electromagnet with the poles assuming opposite magnetic polarities. During one complete excitation cycle, the magnetic polarity changes from zero to maximum in one direction, to zero and reversing to maximum in the opposite direction, returning to zero.

The drum or wound rotor is shown in figure 19-4. This type of rotor is used in most synchro control transformers. The winding of the wound rotor may consist of three coils, so wound that their axes are displaced from each other by 120 degrees. One end of each coil terminates at one of three sliprings on the shaft, while the other ends are connected together. Synchro windings of this type are called Y-connected. In other wound rotors, a single coil of wire or group of coils is connected in series to produce either a concentrated winding effect, or the same distributed winding effect as that of the salient-pole rotor.

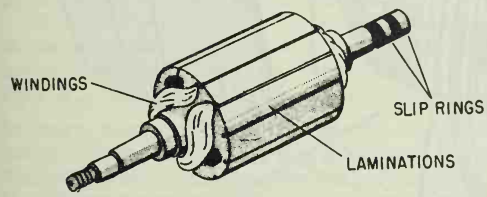


Figure 19-4.—Drum or wound rotor.

Stator Construction

The stator of a synchro is a cylindrical structure of slotted laminations on which three Y-connected coils are wound with their axes 120 degrees apart. Figure 19-5 (A) shows a typical stator assembly and figure 19-5 (B) shows a stator lamination.

Stator windings function as the secondary windings in synchro transmitters and receivers. Normally, stators are not connected directly to an a-c source. Their excitation is supplied by the a-c magnetic field of the rotor.

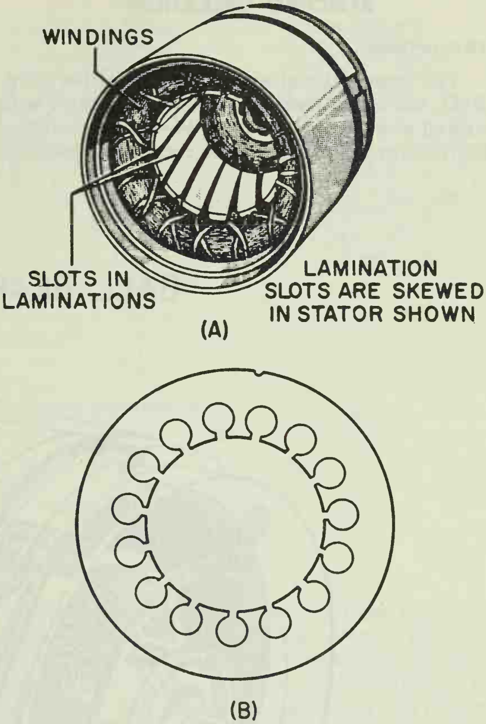


Figure 19-5.—(A) Typical stator; (B) stator lamination.

Some synchros are constructed so that both the stator and rotor may be turned. Connections to the stator of this type are made via sliprings and brushes. In some units, the sliprings are secured to the housing and the brushes turn with the stator. In other units, the brushes are fixed and the sliprings are mounted on a flat insulated plate secured to the stator.

Unit Assembly

The rotor is mounted so that it may turn within the stator. A cylindrical frame houses the assembled synchro. Standard synchros have an insulated terminal block secured to one end of the housing at which the internal connections to the rotor and stator terminate, and to which external connections are made. Special type synchros often have pigtail leads brought out from inside the unit, rather than terminals.

SYNCHRO OPERATION

Transmitters

The conventional synchro transmitter, (fig. 19-6), uses a salient-pole rotor and a stator with skewed slots (fig. 19-5 (A)). When an a-c excitation voltage is applied to the rotor, the resultant current produces an a-c magnetic field. The lines of force, or flux, vary continually in amplitude and direction, and, by transformer action, induce voltages into the stator coils. The effective voltage induced in any stator coil depends upon the angular position of that coil's axis with respect to the rotor axis.

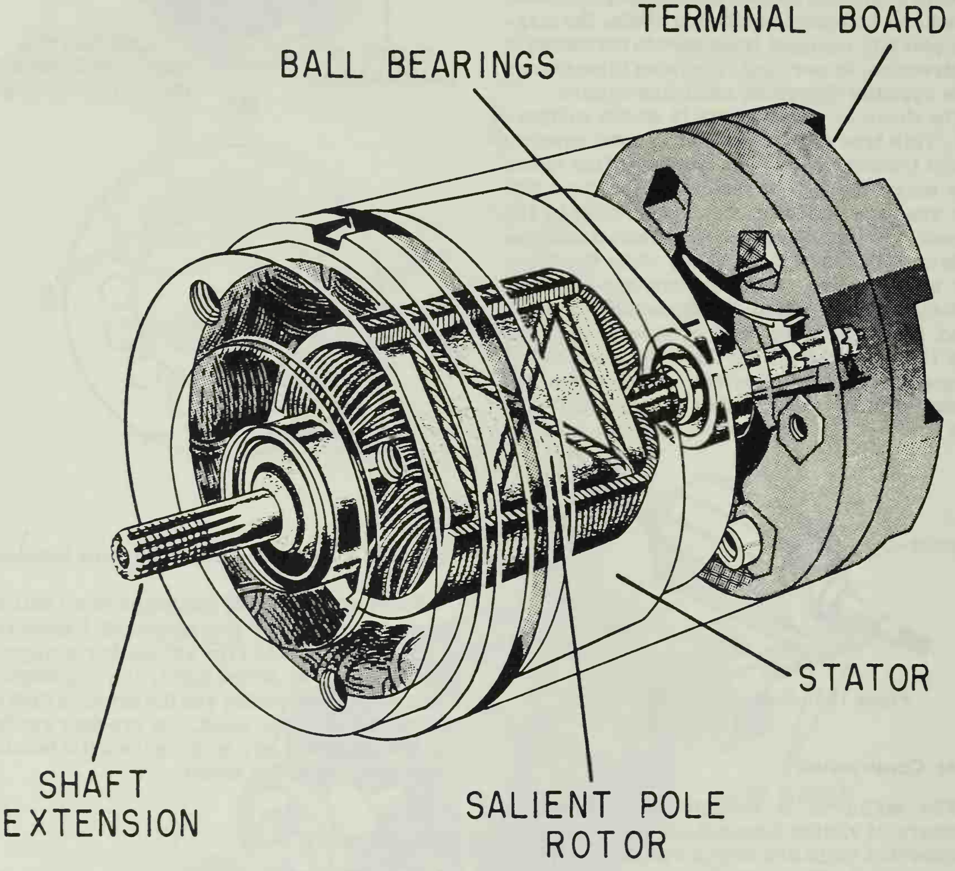


Figure 19-6.–Synchro transmitter or receiver.

When the maximum coil effective (r.m.s.) voltage is known, the effective voltage induced at any angular displacement can be determined. Figure 19-7 is a cross section of a synchro transmitter and shows the effective voltages induced in one stator coil as the rotor is turned to different positions.

The turns ratio between the rotor and stator is such that when single-phase 115-volt power is applied to the rotor, the highest value of effective voltage that will be induced in any one stator coil will be 52 volts. For example, the highest effective voltage that can be induced in stator coil *A* will occur when the rotor is turned

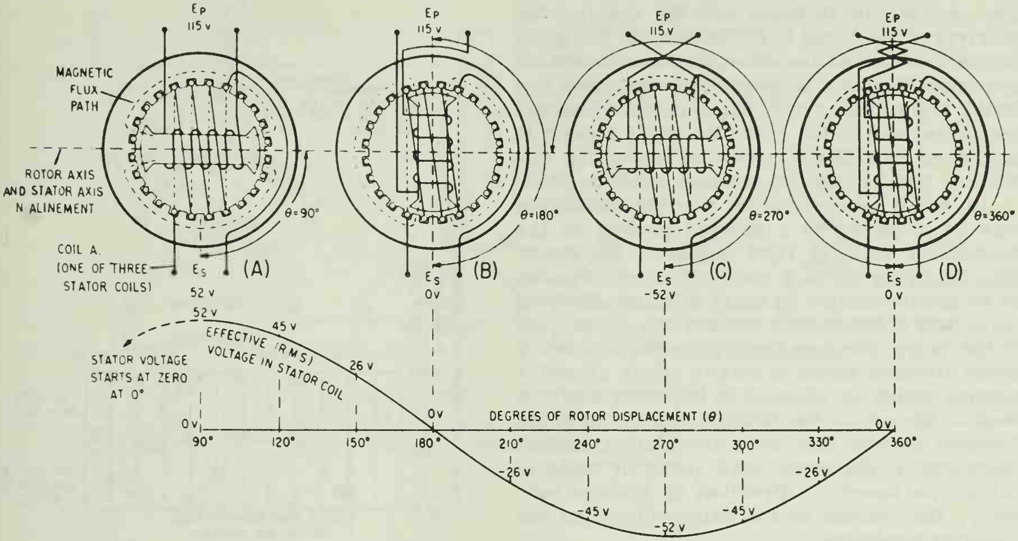

Ep
115 v
MAGNETIC FLUX PATH
ROTOR AXIS AND STATOR AXIS IN ALINEMENT
COIL A (ONE OF THREE STATOR COILS)
Es
52 v
(A)
θ=90°
Ep
115 v
Es
0v
(B)
θ=180°
Ep
115 v
Es
-52 v
(C)
θ=270°
Ep
115 v
Es
0 v
(D)
θ=360°
STATOR VOLTAGE STARTS AT ZERO AT 0°
52 v
45 v
26 v
EFFECTIVE (RMS) VOLTAGE IN STATOR COIL
0 v
0v
DEGREES OF ROTOR DISPLACEMENT (θ)
0v
90°
120°
150°
180°
210°
240°
270°
300°
330°
360°
-26 v
-45 v
-52 v
-45 v
-26 v

Figure 19-7.—Simple synchro transmitter stator voltages.

to angle θ (fig. 19-7 (A)). In this position the rotor axis is in alinement with the axis of winding *A* and the magnetic coupling between the primary and secondary coil *A* is maximum.

The effective voltage, E_S, induced in any one of the secondary windings *A*, *B*, or *C* is approximately equal to the product of the effective voltage, E_p, on the primary; the secondary-to-primary turns ratio, *N*; and the magnetic coupling between primary and secondary which depends upon the cosine of the angle, θ, between the rotor axis and the axis of the corresponding secondary winding. Expressed mathematically,

$$E_s = E_p \times N \times \cos\theta.$$

Therefore, because the effective primary voltage and the turns ratio are constant, the effective secondary voltage varies with angle θ.

Terminal-to-Terminal Stator Voltages

Because the common connection between the stator coils is not accessible, it is possible to measure only the terminal-to-terminal voltages. When the maximum terminal-to-terminal effective voltage is known, the terminal-to-terminal effective voltage for any rotor displacement can be determined. Figure 19-8 shows how these voltages vary as the rotor is turned. Values are above the line when the terminal-to-terminal voltage is in phase with the *R*1 to *R*2 voltage and below the line when the voltage is 180 degrees out of phase with the *R*1 to *R*2 voltage thus negative values indicate a phase reversal. As an example, when the rotor is turned 50 degrees from the reference (zero degree) position, the *S*3 to *S*1 voltage will be about 70 volts and in phase with the *R*1 to *R*2 voltage, the *S*2 to *S*3 voltage will be about 16 volts and also in phase with the *R*1 to *R*2 voltage, and the *S*1 to *S*3 voltage will be about 85 volts, 180 degrees out of phase with the *R*1 to *R*2 voltage. Although the curves of figure 19-8 resemble timegraphs of a-c voltages, they show only the variations in effective voltage amplitude and phase as a function of the mechanical rotor position.

Receivers

Receivers are electrically identical to transmitters of the same size. In some sizes of the 400-cycle standard synchros, the units may be used as transmitters or receivers.

Normally the receiver rotor is unrestrained in movement except for brush and bearing friction. When power is first applied to a system, the transmitter position quickly changes, or if the receiver is switched into the system, the receiver rotor turns to correspond to the position of the transmitter rotor. This sudden motion can cause the rotor to oscillate (swing back and forth) around the synchronous position; should the movement of the rotor be great enough it may even spin. Some method of preventing excessive oscillations or spinning must be used.

In small synchro units, a retarding action may be produced by a shorted winding on the quadrature axis, at right angles to the direct axis. In larger units, a mechanical device known as an inertia damper is more effective. Several variations of the inertia damper are in use. One of the more common types consists of a heavy brass flywheel which is free to rotate around a bushing which is attached to the rotor shaft. A tension spring on the bushing rubs against the flywheel so that they both turn during normal operation. If the rotor shaft turns or tends to change its speed or direction of rotation suddenly, the inertia of the damper opposes the changing condition.

SIMPLE SYNCHRO SYSTEM

A simple synchro transmission system consists of a transmitter connected to a receiver, as shown in figure 19-9. The *R*1 transmitter and *R*1 receiver leads are connected to one side of the a-c supply line and the *R*2 transmitter and *R*2 receiver leads are connected to the other side of the supply line. The stators of both the transmitter and the receiver are connected *S*1 to *S*1, *S*2 to *S*2, and *S*3 to *S*3 so that the voltage in each of the transmitter stator coils opposes the voltage in the corresponding coils of the receiver stator. The voltage directions are indicated by arrows for the instant of time shown by the dot on the sine wave of the rotor supply voltage. The a-c generator symbol inserted in series with each of the synchro windings indicates the presence of a transformer-induced voltage.

The field of the transmitter is alined with the axis of *S*2 (fig. 19-9 (A)) because the transmitter rotor axis is alined with *S*2. Assume for the moment that the receiver rotor is not connected to the single-phase supply. Under this condition the voltage induced in the transmitter stator windings will be impressed on the receiver stator windings through the three leads connecting the *S*1, S2, and *S*3 terminals. Exciting currents that are proportional to the transmitter stator voltages will flow in the receiver stator windings, and the magnetomotive forces produced by these currents will establish a 2-pole field that orients itself in the receiver stator in exactly the same manner that the transmitter field is oriented in its own stator. Thus, if the transmitter field is turned by turning the transmitter rotor, the receiver field will also turn in exact synchronism with the transmitter rotor.

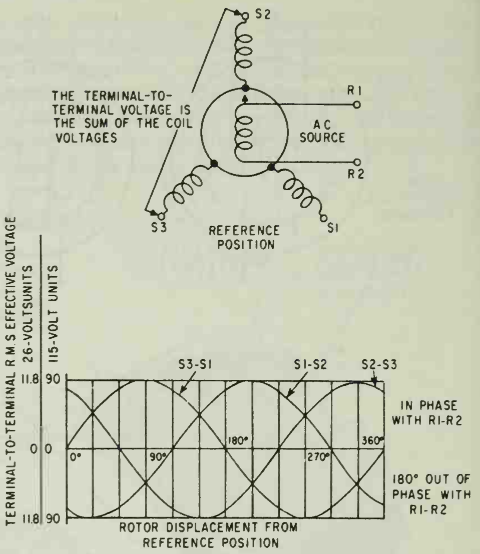

S2
THE TERMINAL-TO-TERMINAL VOLTAGE IS THE SUM OF THE COIL VOLTAGES
R1
AC SOURCE
R2
S3
REFERENCE POSITION
S1
TERMINAL-TO-TERMINAL R.M.S EFFECTIVE VOLTAGE
26-VOLT UNITS
115-VOLT UNITS
S3-S1
S1-S2
S2-S3
11.8
90
0
0
11.8
90
0°
90°
180°
270°
360°
IN PHASE WITH R1-R2
180° OUT OF PHASE WITH R1-R2
ROTOR DISPLACEMENT FROM REFERENCE POSITION

Figure 19-8.—Terminal-to-terminal voltages.

A soft-iron bar placed in a magnetic field will always tend to aline itself so that its longest axis is parallel to the axis of the field. Thus, the salient pole receiver rotor will also aline itself with the receiver field even though the receiver rotor winding is open-circuited. Operation with an open-circuited rotor is not desirable, however, because for a given position of the transmitter rotor and field there are two positions, 180° apart, in which the salient pole receiver rotor may come into alinement with the receiver field. This difficulty is eliminated by energizing the receiver rotor with alternating current of the same frequency and phase as that supplied to the transmitter rotor. Now the receiver rotor electromagnet comes into alinement with the receiver field in such a position as to always aid the magnetomotive forces of the three windings of the receiver stator. A rotor position in which the magnetomotive force of the rotor opposes the magnetomotive forces of the stator would not be stable. For example, a compass

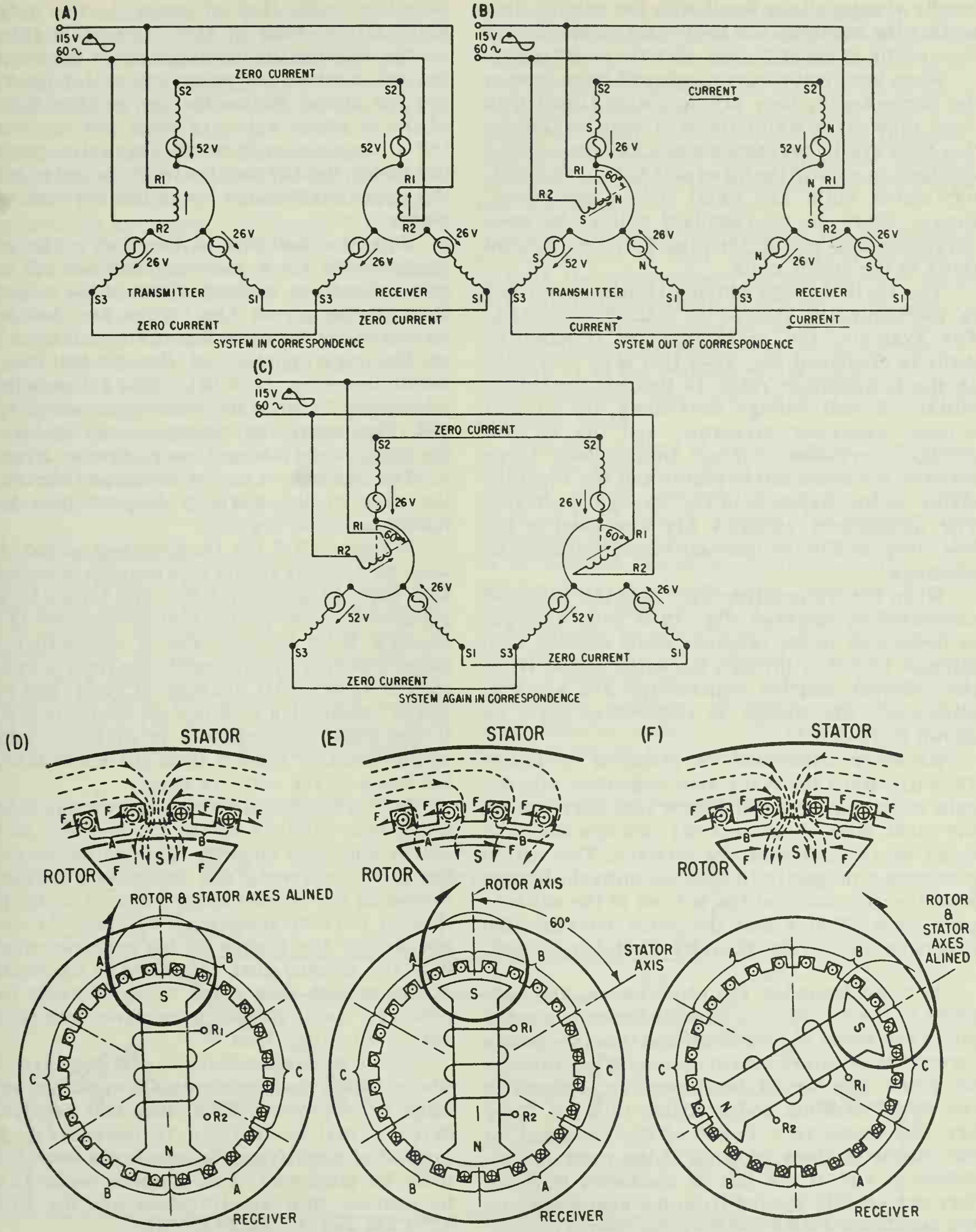

(A)
115 V
60 ~
ZERO CURRENT
S2
S2
52 V
52 V
R1
R1
R2
R2
26 V
26 V
26 V
26 V
S3
TRANSMITTER
S1
S3
RECEIVER
S1
ZERO CURRENT
ZERO CURRENT
SYSTEM IN CORRESPONDENCE
(B)
115 V
60 ~
CURRENT
S2
S2
S
N
26 V
52 V
R1
60°
R2
N
S
N
R1
S
R2
26 V
26 V
26 V
S
52 V
N
N
S
S3
TRANSMITTER
S1
S3
RECEIVER
S1
CURRENT
CURRENT
SYSTEM OUT OF CORRESPONDENCE
(C)
115 V
60 ~
ZERO CURRENT
S2
S2
26 V
26 V
R1
60°
R2
60°
R1
R2
26 V
26 V
52 V
52 V
S3
S1
S3
ZERO CURRENT
S1
ZERO CURRENT
SYSTEM AGAIN IN CORRESPONDENCE
(D)
STATOR
F
F
F
F
A
B
S
F
F
ROTOR
ROTOR & STATOR AXES ALINED
A
B
S
R1
C
C
R2
N
B
A
RECEIVER
(E)
STATOR
F
F
F
A
B
S
F
ROTOR
ROTOR AXIS
60°
STATOR AXIS
A
B
S
R1
C
C
R2
N
B
A
RECEIVER
(F)
STATOR
F
F
F
F
B
C
S
F
F
ROTOR
ROTOR & STATOR AXES ALINED
A
B
S
C
C
R1
N
R2
B
A
RECEIVER

Figure 19-9.—Development of torque in a synchro.

needle always alines itself with the earth's field so that the north pole of the needle points toward the south magnetic pole (north geographic).

When both rotors are displaced from zero by the same angle, they are properly alined with their respective stator fields. Under this condition they are in correspondence and the induced voltages in each of the three pairs of corresponding stator coils are equal and in opposition. Hence, there is no resultant voltage between corresponding stator terminals and no current flows in the stator coils.

The angle through which a transmitter rotor is mechanically rotated is called a SIGNAL. For example, the angle that the transmitter rotor is displaced (fig. 19-9 (B)) is 60°. As soon as the transmitter rotor is turned, the transmitter *S*2 coil voltage decreases, the *S*1 coil voltage reverses direction, and the *S*3 coil voltage increases. Current immediately flows between the transmitter stator and the receiver stator in the direction of the stronger voltages. The unbalanced voltages are absorbed in the line drop and in the internal impedances of the windings.

When the transmitter (fig. 19-9 (A)) is turned clockwise 60 degrees (fig. 19-9 (B)), a torque is developed in the receiver rotor causing it to attempt to follow through the same angle. When the receiver and the transmitter are again in alinement, the torque is reduced to zero, as shown in 19-9 (C).

Receiver alinement is pictured in figure 19-9 (D). Here the rotor axis coincides with the axis of the stator field. Notice that currents on the right side of the vertical axis are back and those on the left side are forward. This action produces a magnetic field as shown by the letters S at the top and N at the bottom of the salient-pole rotor. Notice that the rotor current also produces the same polarity (left-hand rule).

For the balanced condition shown, the currents in the conductors opposite the salient rotor poles are equal in magnitude and flow in opposite directions on either side of the centerline through the poles. The forces developed are pictured in the detail drawing above figure 19-9 (D). They are developed as a result of the crowding of the magnetic lines of force at the right of conductor A and at the left of conductor B. Since they are equally spaced from the centerline, no net unbalance exists and the rotor torque is zero.

In figure 19-9 (E), the receiver stator field is rotated clockwise 60 degrees so that its axis coincides with that of phase A. The rotor is deliberately held in the vertical position to enable showing the development of the torque on the rotor when the rotor and stator field axes are not alined. Notice that currents to the right of the A-phase axis are back and those to the left of the axis are forward. This action produces the stator field across the rotor and extends from the upper right to the lower left portions of the stator.

Now the currents in the stator conductors opposite the rotor salient poles are all in the same direction on both sides of the centerline through the poles. The forces are unbalanced as shown by the crowding of the magnetic lines on the right portion of the conductors. (See detail above fig. 19-9 (E).) This action indicates a tendency to force the stator conductors to the left. The equal and opposite reaction force on the rotor tends to turn it in a clockwise direction.

The amount of torque developed varies with the sine of the angle of displacement and is maximum at 90 degrees.

In figure 19-9 (F), the rotor has turned clockwise 60 degrees and its axis is again in alinement with that of the stator field. The torque is again reduced to zero. Notice that the current in conductors B is forward and in conductors C is back. The flux lines crowd to the right of conductors B (see detail drawing at right) and to the left of conductors C. Since the currents in B and C are equal and opposite in direction and are symmetrically spaced about the rotor axis, the net force on the rotor is zero.

As a receiver approaches correspondence, the stator voltages of the transmitter and receiver approach equality. This action decreases the stator currents and produces a decreasing torque on the receiver that reduces as the position of correspondence is reached. At correspondence, the torque on the receiver rotor is only the amount that is caused by the tendency of the salient-pole rotor to aline itself in the receiver field. Hence, a receiver can position only a very light load.

Synchro transmission systems are used where torque requirements are small. However, when drive power heavier than that required to drive a dial or pointer is necessary, some method of amplifying the synchro's weak torque must be employed. Two common methods used to provide this amplification are the SERVO SYSTEM and the AMPLIDYNE .

Many installations connect one transmitter to several receivers in parallel. This procedure requires a transmitter large enough to carry the total load current of all the receivers. All the *R*1 rotor leads are connected to one side of the a-c power supply, and all the *R*2 rotor leads are connected to the other side of the supply. The receiver stator leads are connected lead for lead to the transmitter stator leads.

The sizes of Navy synchro transmitters are designated by numbers. Synchro transmitters in general use are sizes 1, 5, 6, and 7. Synchro receivers in general use are sizes 1 and 5. A size-1 transmitter can control one or two size-1 receivers; a size-5 transmitter can control two size-5 receivers; a size-6 transmitter can control as many as nine size-5 receivers; and a size-7 transmitter can control as many as eighteen size-5 receivers.

Synchros employed in airborne equipments are usually designed for 400-cycle operation, and as a result, are considerably lighter in weight and smaller in size than those that operate with 60-cycle line voltages.

Reversing Direction of Receiver Rotation

When the teeth of two mechanical gears are meshed and a turning force is applied, the gears turn in opposite directions. If a third gear is added, it turns in the same direction as the first. This is important here because synchro receivers are often connected through a train of mechanical gears to the device which they operate, and whether or not force is applied to the device in the same direction as that in which the receiver rotor turns depends on whether the number of gears in the train is odd or even.

The important thing, of course, is to move the dial or other device in the proper direction, and even when there are no gears involved, this may be opposite to the direction in which the receiver rotor of a normally connected system would turn.

Either of these two factors, and sometimes a combination of both, may make it necessary to have the transmitter turn the receiver rotor in a direction opposite to that of its own rotor. This is accomplished by reversing the *S*1 and *S*3 connections of the transmitter-receiver system, so that *S*1 of the transmitter is connected to *S*3 of the receiver and vice versa. This is shown in figure 19-10.

With both rotors at zero degrees, conditions within the system remain the same as during normal stator connections, since the rotor coupling to *S*1 and *S*3 is equal. But suppose that the transmitter rotor is turned counterclockwise to 60 degrees, as shown in figure 19-10. In the transmitter, maximum rotor coupling induces maximum voltage across *S*1, which causes maximum current to flow through *S*3 in the receiver. The magnetic forces produced turn the receiver rotor clockwise into line with *S*3, the rotor's 300-degree position, at which point the rotor again induces voltages in its stator coils which equal those of the transmitter coils to which

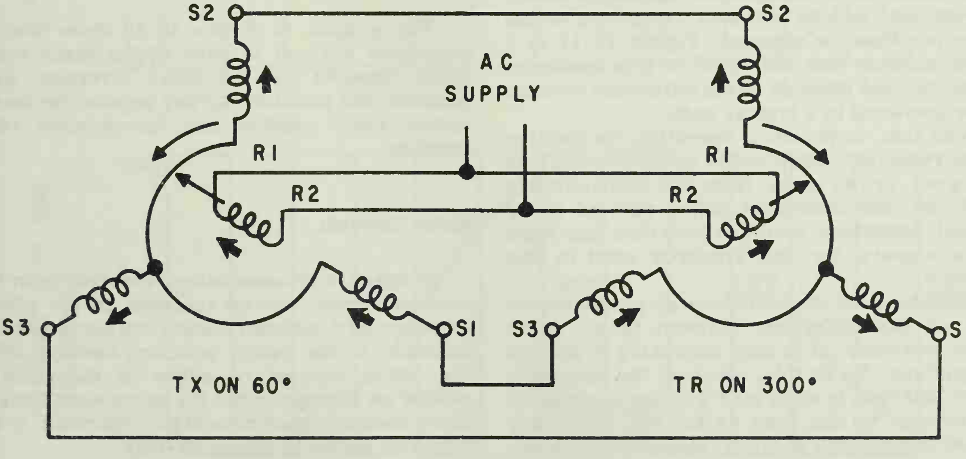


Figure 19-10.—Effect of reversing S1 and S3 connections between the transmitter and receiver.

they are connected. Notice that only the direction of rotation changes, not the amount; the 300-degree position is the same as the minus 60-degree position.

It is important to emphasize that the *S*1 and *S*3 connections are the only ones ever interchanged in a standard synchro system. Since *S*2 represents electrical zero, changing the *S*2 lead would introduce 120-degree errors in indication, and also reverse the direction of rotation.

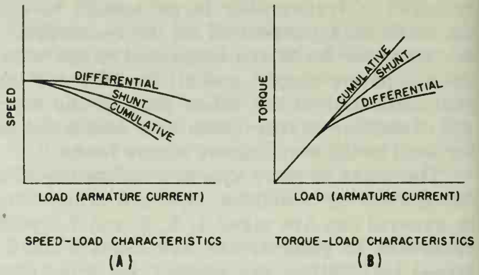
Stator Currents

Whenever the rotors of two interconnected synchros are in different positions, current flows in the stator windings. The amount of current flowing in each stator lead depends on the difference between the voltages induced in the two coils to which that lead connects. This voltage unbalance, in turn, depends on two things -- (1) the actual positions of the rotors, and (2) the difference between the two positions.

To observe the effect of the latter, suppose that an ammeter is inserted in any one of the stator leads, the *S*2 lead for example. Also, suppose that the two rotors are held so that there is a constant difference between their positions while they are rotated together until a point is found at which the ammeter indicates maximum stator current. If the difference between rotor positions is then increased and the rotation repeated, a different maximum reading is obtained. Each time the difference between rotor positions is changed, the maximum stator current that can be obtained by varying actual rotor positions is changed. Figure 19-11 is a graph showing how the value of this maximum stator current depends on the difference between rotor positions in a typical case.

Note that, in practical operation, the position of the receiver's shaft would never be more than a degree or so away from the transmitter's shaft, so that maximum stator current under normal conditions would be less than one-tenth of an ampere for the synchros used in this example.

To see how the actual rotor positions, as well as the difference between them, affect stator currents, it is only necessary to make a comparison. To do this, compare the maximum stator current in each lead with the strength of the current in that lead as the two rotors are turned through 360 degrees, maintaining the difference in rotor position with which the maximum stator current was established.



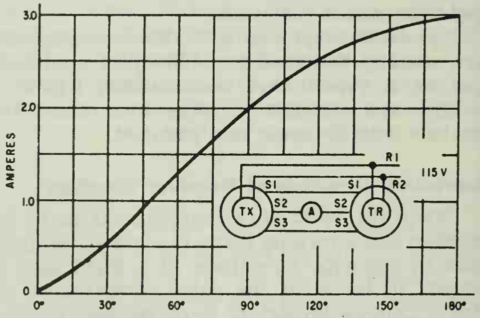


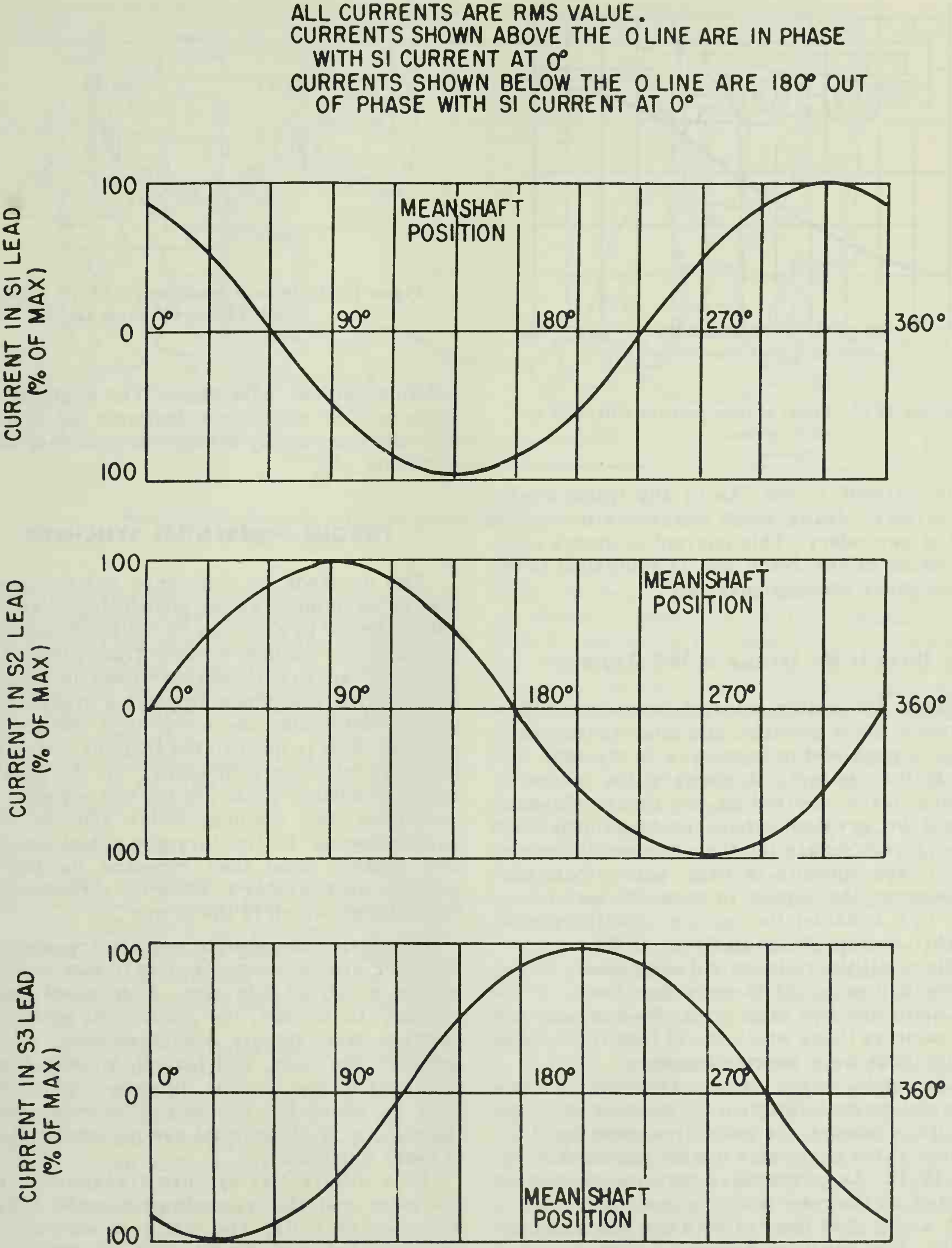
Figure 19-11.—Effect of rotor position difference on maximum stator current.

The graphs in figure 19-12 show how the maximum current in each of the three stator leads depends on the mean (average) shaft position; the position halfway between the transmitter rotor position and the receiver rotor position.

Rotor Currents

A synchro transmitter or receiver acts like a transformer, and an increase in the stator, or secondary current, results in a corresponding increase in the rotor, primary, current. When the rotor current of either of the units is plotted on a graph under the same conditions as those used for maximum stator currents, it appears as shown in figure 19-13.

Although all three stator currents are zero when the shafts are in the same positions, the



ALL CURRENTS ARE RMS VALUE.
CURRENTS SHOWN ABOVE THE 0 LINE ARE IN PHASE WITH S1 CURRENT AT 0°
CURRENTS SHOWN BELOW THE 0 LINE ARE 180° OUT OF PHASE WITH S1 CURRENT AT 0°

Figure 19-12.—Effect of actual rotor position on individual stator current.

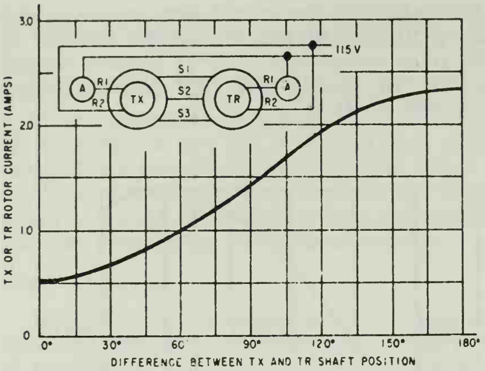


Figure 19-13.—Effect of rotor position difference on rotor current.

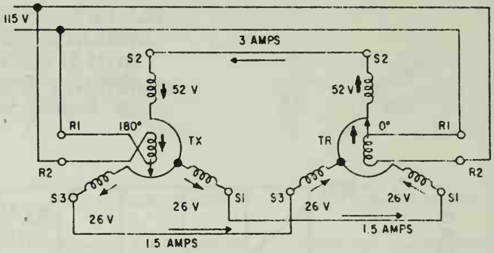


Figure 19-14.—Internal conditions in TX-TR system when TX and TR rotors are 180° apart.

rotor current is not. As in any transformer, the primary draws some current with no load on the secondary. This current produces magnetization of the rotor and is equivalent to the transformer exciting current.

Why There Is No Torque at 180 Degrees

Since the stator current increases with a change in rotor position, and since the magnetic field of each stator increases in strength with the stator current, it appears the torque or turning force exerted by the receiver's shaft should be greatest when the transmitter and receiver rotors are 180 degrees apart. However, exactly the opposite is true. Under these circumstances the torque is zero. To understand this, first consider the current conditions in the synchro system shown in figure 19-14.

Since all the voltages aid each other, strong currents flow in all three stator leads. If the two units are the same size, the currents are the same as those which would flow if the three stator leads were shorted together.

Obviously, these strong currents produce powerful magnetic forces. To see why no torque results, consider the polarities existing in the system at the particular instant assumed in figure 19-15. As powerful as they are, the forces exerted on the rotor work against each other in such a way that their effects are equal and opposite. The resulting torque is zero. In actual situations, the two shafts do not stay in these positions unless held there. The slightest displacement of either one destroys the balance, and they are rapidly brought into corresponding positions.

TORQUE DIFFERENTIAL SYNCHROS

The demands on a synchro system are not always as simple as the positioning of an indicating device in response to the information received from a single source (transmitter). For example, an error detector used in checking fire-control equipment employs a synchro system to determine the error in a gun turret's position with respect to the training order supplied by a dummy director. To do this, the synchro system must accept two signals, one containing the training order and the other corresponding to the turret's actual position. The system must then compare the two and position an indicator to show the difference between them, which is the error.

Obviously, the simple synchro transmitter-receiver system considered up to now could not handle a job of this sort. A different type of synchro is needed, one which can accept two position-data signals simultaneously, add or subtract the data, and furnish an output proportional to the sum or difference of the two. This is where the synchro differential enters the picture. A differential can perform all three of these functions.

In a differential synchro transmitter, both the rotor and stator windings consist of three Y-connected coils. The stator is normally the primary, and receives its excitation from a synchro transmitter. The voltages appearing across

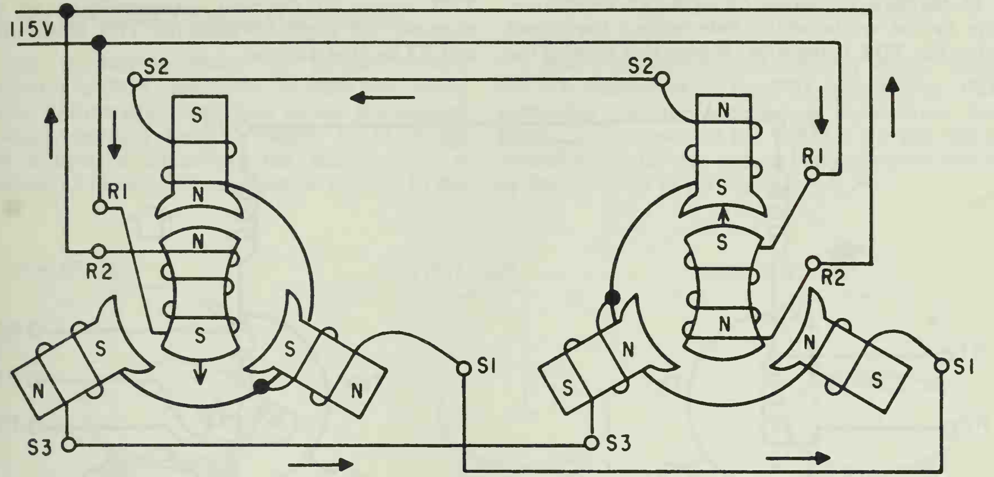


Figure 19-15.—Magnetic polarities at a particular instant when TX and TR rotors are 180° apart.

the differential's rotor terminals are determined by the magnetic field produced by the stator currents AND the physical position of the rotor. The magnetic field created by the stator currents assumes an angle corresponding to that of the magnetic field in the transmitter supplying the excitation. If the rotor position changes, the voltages induced into its windings also change, so that the voltages present at the rotor terminals change.

Differential Receivers

As torque receivers were previously compared to torque transmitters, so may torque differential receivers be compared to torque differential transmitters. Both rotor and stator receive energizing currents from torque transmitters. The two resultant magnetic fields interact and the rotor turns.

In a torque differential synchro system, the system will consist either of a torque transmitter (TX), a torque differential transmitter (TDX), and a torque receiver (TR); or the system may consist of two torque transmitters (TX) and one torque differential receiver (TDR).

TX-TDX-TR Synchro System

Assume that the stator leads of a torque transmitter are connected to the corresponding stator leads of a torque differential transmitter, as shown in figure 19-16. The resultant stator m.m.f., shown by the open arrow, produced in the TX directly opposes the TX rotor m.m.f., shown by the solid arrow. Corresponding stator coils of the two units are in series; for example, *S*2 of TX is in series with *S*2 of the TDX, and the current flow produces a resultant stator m.m.f. of equal strength in the TDX. However, currents in corresponding stator coils of the TDX are opposite in direction. The direction of the stator m.m.f. in the TDX is therefore opposite to the direction of the TX stator m.m.f., but identical to the direction of its rotor m.m.f.

The TDX rotor coils are angularly spaced 120 degrees apart, in the same manner as the TX stator coils. The TDX stator m.m.f. is identical to the TX rotor m.m.f., neglecting small circuit losses.

Before considering such an arrangement, however, it must be made clear that the controlling relationship in the TDX is the position of the TDX stator field with respect to the rotor, not with respect to the TDX stator. Suppose that the TX rotor in the previous example is turned to 75 degrees, and the TDX rotor to 30 degrees, as shown in figure 19-17. The TDX stator field is now positioned at 75 degrees with respect to *S*2, but the angle at which it cuts the TDX rotor is 45 degrees, using the $R2$ axis as a reference. This is the angle which determines the signal which the TDX transmits. Notice that turning the TDX rotor 30 degrees counterclockwise decreased the angle between the TDX stator field and $R2$ by that amount.

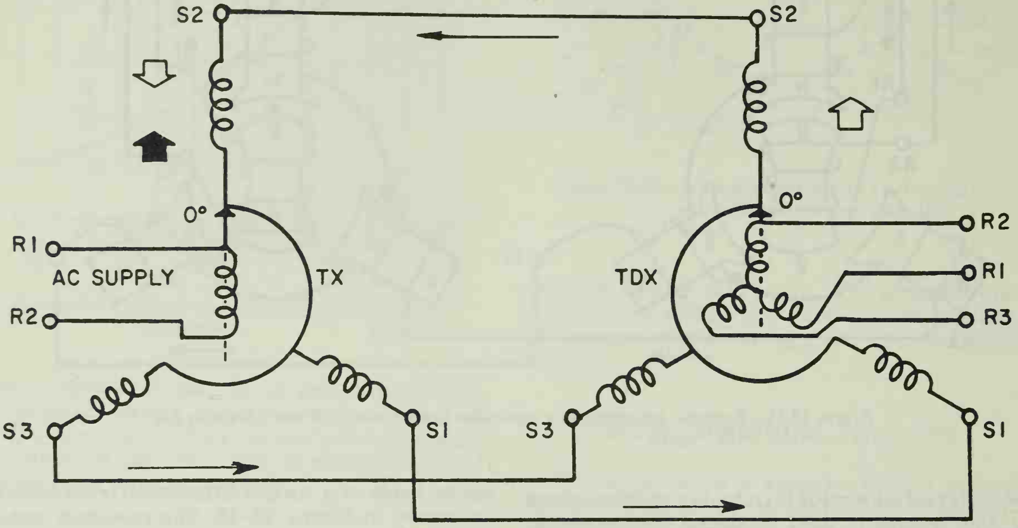

S2
S2
0°
0°
R1
AC SUPPLY
R2
TX
TDX
R2
R1
R3
S3
S1
S3
S1

Figure 19-16.—Position of TDX stator m.m.f. when TX rotor is at zero degree.

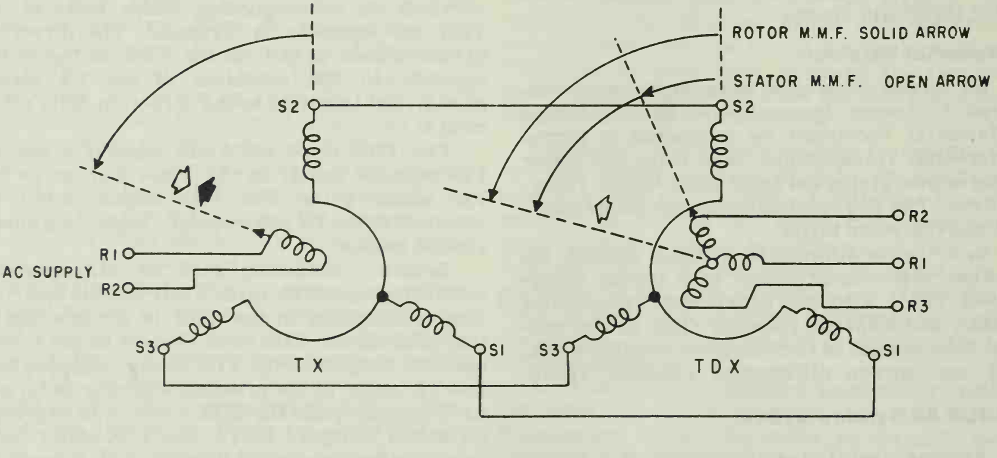

ROTOR M.M.F. SOLID ARROW
STATOR M.M.F. OPEN ARROW
S2
S2
R1
AC SUPPLY
R2
R2
R1
R3
S3
S1
S3
S1
TX
TDX

Figure 19-17.—Rotating TDX stator field by turning the TX rotor.

How the Differential Transmitter Subtracts

The manner in which the torque system containing a TDX subtracts or adds two inputs can be figuratively described as the positioning of magnetomotive forces. Figure 19-18 shows such a system connected for subtraction. A mechanical input of 75 degrees is applied to the TX and converted to an electrical signal which the TX transmits to the TDX stator. The TDX subtracts its own mechanical input from this signal, and transmits the result to the TR, which indicates the torque system's mechanical output by the position of its rotor.

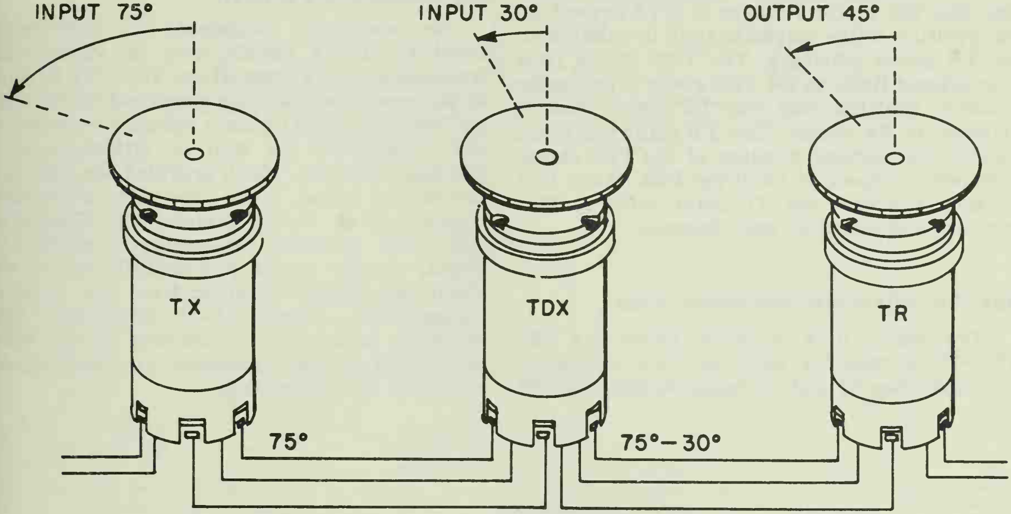

INPUT 75°
INPUT 30°
OUTPUT 45°
TX
TDX
TR
75°
75°–30°

Figure 19-18.–Subtraction with TDX.

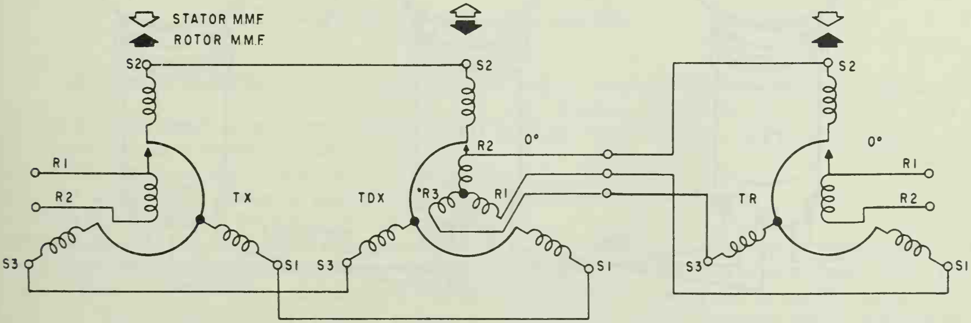

STATOR MMF
ROTOR MMF
S2
S2
S2
R1
R2
TX
TDX
R2
0°
R3
R1
0°
TR
R1
R2
S3
S1
S3
S1
S3
S1

Figure 19-19.–Magnetomotive force positions in TX-TDX-TR system with all rotors at zero degree.

To understand how this result is accomplished, first consider the conditions in a TX-TDX-TR system when the TX and TDX rotors are turned to zero degrees, as in figure 19-19.

It has been shown how torque is developed in a synchro receiver to bring its rotor into a position which corresponds to that of an associated transmitter. The rotor voltages of the TDX depend upon the position of the magnetic field in relation to the rotor windings in the same way that the stator voltages of a TR depend on the position of the magnetic field in relation to the TR stator windings. The TDX stator field axis orients itself in the TDX stator in the same relative position that the TX rotor axis is oriented in its stator. The TR rotor therefore follows the angular position of the TDX stator field with respect to *R*2 of the TDX. Since this is zero degrees, the TR rotor turns to that position, and indicates zero degrees.

How the Differential Transmitter Adds

Frequently, it is necessary to set up a TX-TDX-TR system for addition. This is done by reversing the *S*1 and *S*3 leads between the TX and TDX stators, and the *R*1 and *R*3 leads between the TDX rotor and the TR. With these connections the system behaves as illustrated in figure 19-20. The 75-and 30-degree mechanical inputs, applied respectively to the rotor of the TX and the rotor of the TDX, are added and transmitted to the TR, whose rotor provides an output equal to their sum by turning to 105 degrees.

The Differential Receiver

As previously explained, the differential receiver differs chiefly from the differential transmitter in its application. The TDX in each of the previous examples combined its own input with the signal from a synchro transmitter and transmitted the sum or difference to a synchro receiver, which provided the system's mechanical output. In the case of the differential receiver in a torque system, the differential unit itself provides the system's mechanical output, usually as the sum or difference of the electrical signals received from two synchro transmitters. Figure 19-21 illustrates this operation in a system consisting of two TX's and a TDR (torque differential receiver) interconnected for subtraction.

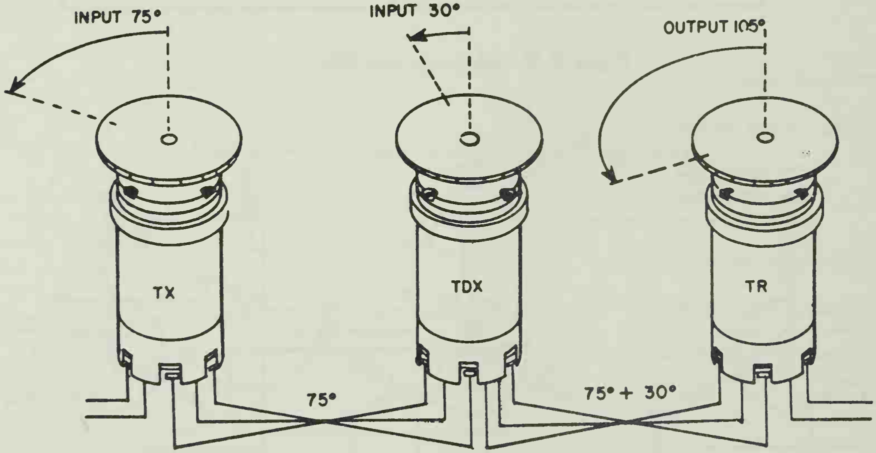


Figure 19-20.–Addition with TDX.

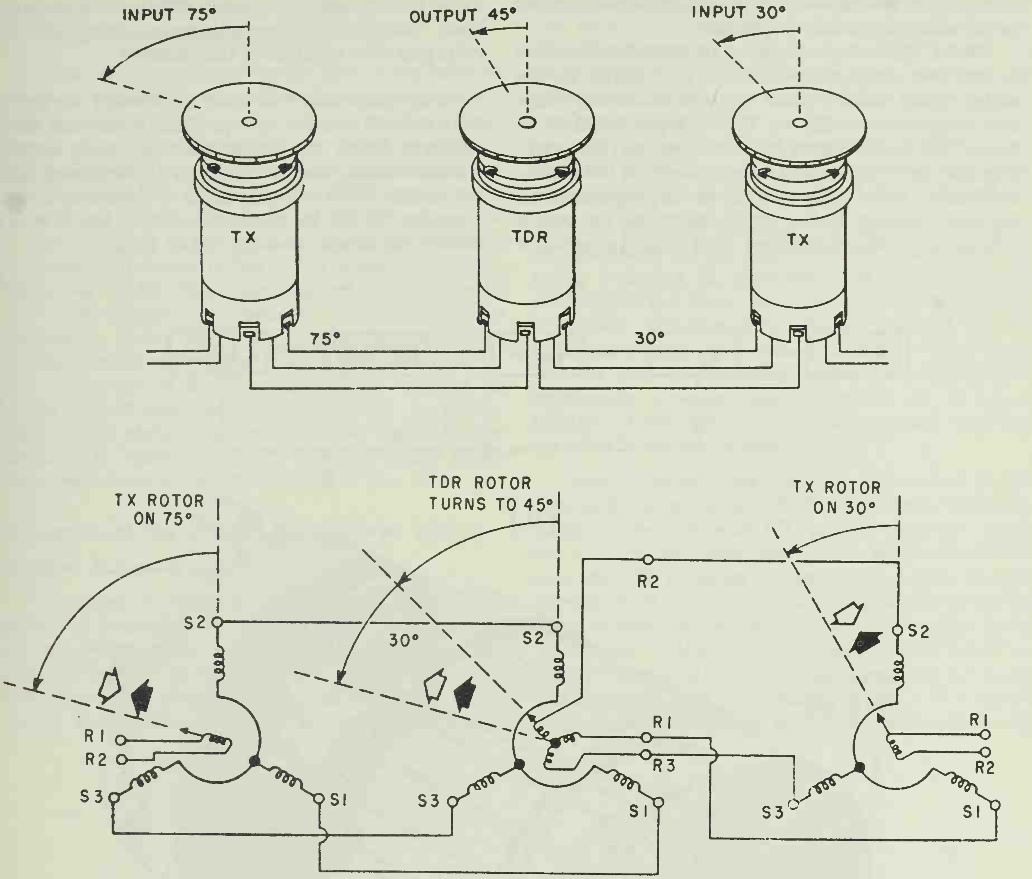

INPUT 75°
OUTPUT 45°
INPUT 30°
TX
TDR
TX
75°
30°
TX ROTOR ON 75°
TDR ROTOR TURNS TO 45°
TX ROTOR ON 30°
30°
S2
S2
S2
R2
R1
R2
S3
S1
S3
S1
R1
R3
S3
S1
R1
R2

Figure 19-21.—Subtraction with TDR.

CONTROL SYNCHRO SYSTEMS

There is wide usage of synchros as followup links in automatic control systems. Synchros alone do not possess sufficient torque (turning power), to rotate such loads as radar antennas or gun turrets; however, they can control power amplifying devices, which in turn can move these heavy loads. For such applications, servo motors are used. They are placed in a closed-loop servo mechanism employing a special type of synchro called a synchro control transformer (CT) to detect the difference (error) signal between the input and output of the loop. A block diagram of such 'a transformer is shown in figure 19-22 (A). Figure 19-22 (B) is a phantom view of a typical transformer, CT, with a drum rotor.

The Control Transformer

The distinguishing unit of any synchro control system is the control transformer, CT. The CT is a synchro designed to supply, from its rotor terminals, an a-c voltage whose magnitude and phase is dependent on the rotor position, and on the signal applied to the three stator windings. The behavior of the CT in a system differs from that of the synchro units previously considered in several important respects.

Since the rotor winding is never connected to the a-c supply, it induces no voltage in the stator coils. As a result, the CT stator currents are determined only by the voltages applied to them. The rotor itself is wound so that its position has very little reflected effect on the stator currents. Also, there is never any appreciable current flowing in the rotor, because its output voltage is always applied to a high-impedance load, 10,000 ohms or more. Therefore, the rotor does not turn to any particular position when voltages are applied to the stators.

The rotor shaft of a CT is always turned by an external force, and produces varying output voltages from its rotor winding. Like synchro transmitters, the CT requires no inertia damper, but unlike either transmitter or receivers, rotor coupling to *S*2 is minimum when the CT is at electrical zero. (See fig. 19-2 (D)).

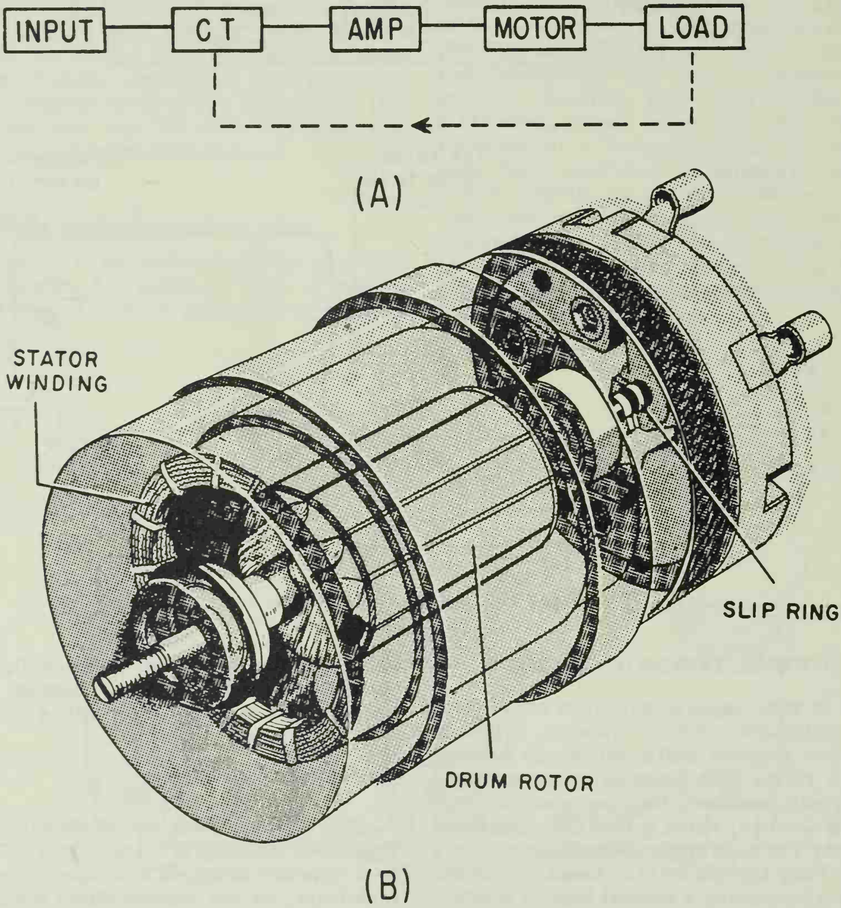


Figure 19-22.—(A) Block diagram with control transforming; (B) typical control transformer.

Relationship of the Stator Voltages in a CT to the Resultant Magnetic Field

When current flows in the stator circuits of a CT, a resultant magnetic field is produced. This resultant field can be rotated by the signal from a synchro transmitter, or synchro differential transmitter, in the same manner as the resultant stator field of the TDX previously considered. When the field of the CT stator is at right angles to the axis of the rotor winding, the voltage induced in the rotor winding is zero. When the stator field and the rotor's magnetic axis are alined, the induced rotor voltage is maximum. Since the CT's output is expressed in volts, it is convenient to consider its operation in terms of stator voltages as well as in terms of the position of the resultant magnetic field, but it should be remembered that it is the ANGULAR POSITION, with respect to the rotor axis, that determines the output of the CT.

Operation of the Control Transformer With a Synchro Transmitter

Consider the conditions existing in the system shown in figure 19-23, where a CT is connected for operation with a CX (control transmitter) and the rotors of both units are positioned at zero degrees. The relative phases of the individual stator voltages with respect to the *R*1 to *R*2 voltage of the transmitter are indicated by the small arrows. The resultant stator field of the CT is shown in the same manner as for the TDX. With both rotors in the same position, the CT stator field is at right angles to the axis of the rotor coil. Since no voltage is induced in a coil by an alternating magnetic field perpendicular to its axis, the output voltage appearing across the rotor terminals of the CT is zero.

Now assume that the CT rotor is turned to 90 degrees, as in figure 19-24, while the CX rotor remains at zero degrees. Since the CT's rotor position does not affect stator voltages or currents, the resultant stator field of the CT remains alined with *S*2. The axis of the rotor coil is now in alinement with the stator field. Maximum voltage, approximately 55 volts, is induced in the coil and appears across the rotor terminals as the output of the CT.

Next, assume the CX rotor is turned to 180 degrees, as in figure 19-25. The electrical positions of the CX and CT are 90 degrees apart, the CT stator field and rotor axis are alined, and the CT's output is maximum again, but the direction of the rotor's winding is now reversed with respect to the direction of the stator field. The phase of the output voltage is therefore opposite to that of the CT in the preceding example. This means that the phase of the CT's output voltage indicates the direction in which the CT

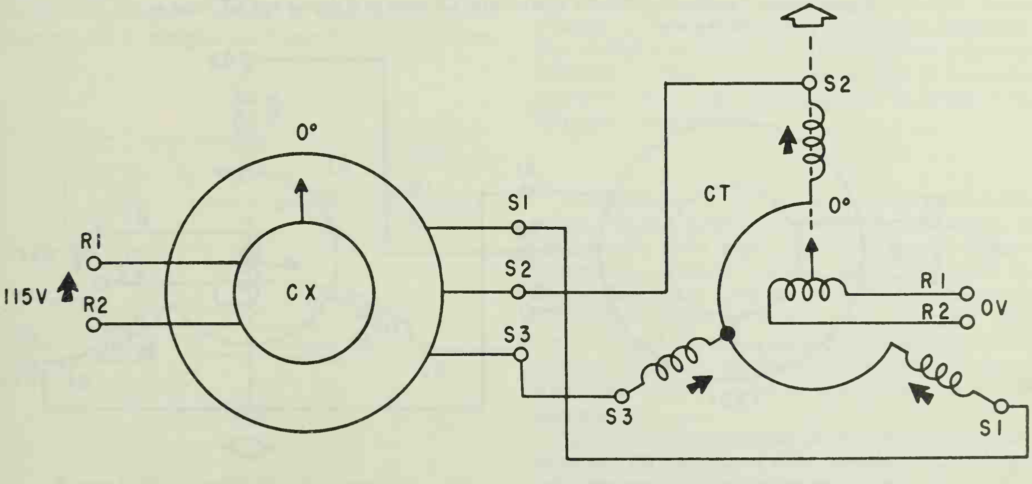


Figure 19-23.—Conditions in CX-CT system with rotors in correspondence.

rotor is displaced with respect to the position-data signal applied to its stators.

It is evident that the CT's output can be varied by rotating either its rotor or the position-data signal applied to its stators. It can also be seen that the magnitude and phase of the output depend on the relationship between signal and rotor rather than on the actual position of either.

Servomechanisms

In the operation of electrical and electronic equipment, it is often necessary to operate a mechanical load that is remotely located from its source of control. Examples of this are the movement of heavy radar antennas or small indicator motors. The mechanical load may require either high or low torque movement.

It can be stated that a servomechanism is an electromechanical device that positions an

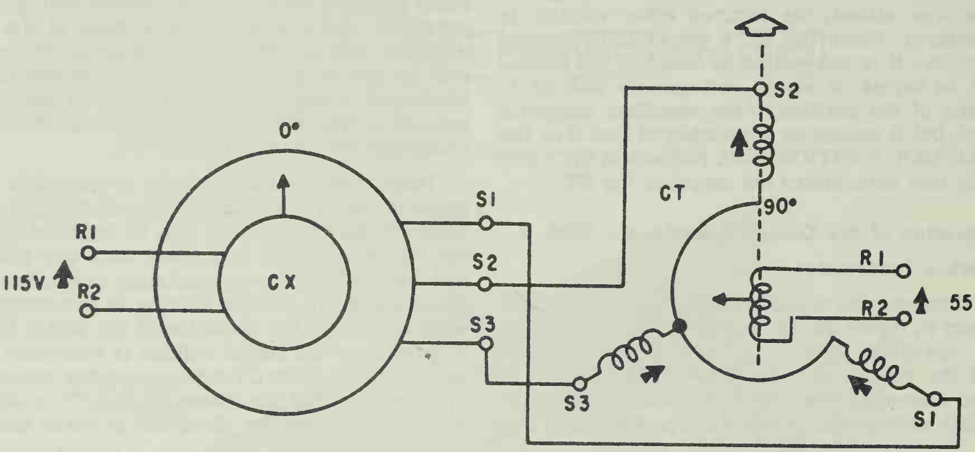


Figure 19-24.—Conditions in CX-CT system with CX rotor at 0 degree and CT rotor at 90 degrees.

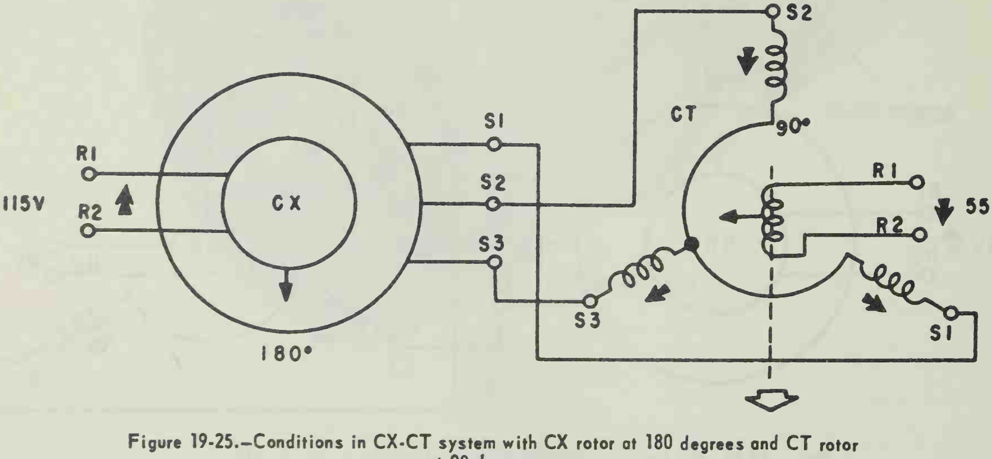


Figure 19-25.—Conditions in CX-CT system with CX rotor at 180 degrees and CT rotor at 90 degrees.

object in accordance with a variable signal. The signal source may be capable of supplying only a small amount of power. A servomechanism operates to reduce difference (error) between two quantities. These quantities are usually the CONTROL DEVICE position and the LOAD position.

The essential components of a servomechanism system are the INPUT CONTROLLER and OUTPUT CONTROLLER.

INPUT CONTROLLER

The input controller provides the means whereby the human operator may actuate or operate the remotely located load. This may be achieved either mechanically or electrically. Electrical means are most commonly used. Synchro systems and bridge circuits are most widely used for input control of servomechanism systems.

OUTPUT CONTROLLER

The output controller of a servomechanism system is the component or components in which power amplification and conversion occur. This power is usually amplified by vacuum-tube amplifiers or magnetic amplifiers. In many applications a combination of these are used. The power from the amplifier is then converted by the servomotor into mechanical motion of the direction required to produce the desired function. This sequence of functions is shown in figure 19-26. The figure shows a simplified block diagram of a simple servomechanism system.

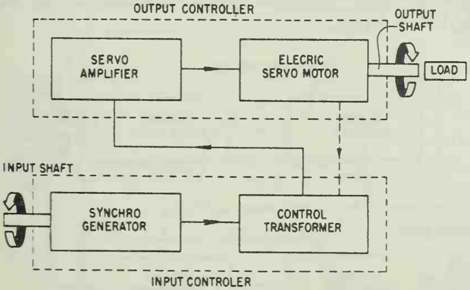


Figure 19-26.—Simplified block diagram of a servomechanism.

OPERATION OF BASIC SERVOMECHANISM

The block diagram of figure 19-26, is shown schematically in figure 19-27. Its basic principles of operation are as follows:

The INPUT CONTROLLER, which consists of a synchro control transmitter (CX) and a synchro controller transformer (CT), originates, or commands, the system movement. The CX's rotor is attached to a shaft, which is turned by hand or by a controlling mechanical device. Movement of the CX rotor from its electrical zero will cause an unbalance of voltages in the stator windings $S2$, $S1$, and $S3$. (This was explained under the heading, Control Synchro Systems.) A voltage is induced in the rotor of the control transformer. Its MAGNITUDE depends on the AMOUNT of displacement of the CX rotor; its PHASE RELATIONSHIP depends on the DIRECTION of displacement from electrical zero. This voltage represents the ERROR voltage. Since a control transformer is not designed to furnish enough power to drive a load of any significant size, the error voltage must be amplified before it is powerful enough to drive the servomotor, and thus move the load.

The servoamplifier, as stated before, may be a vacuum-tube type or magnetic type. In many cases, it is a combination of both. In the combination type, the vacuum-tube section amplifies the ERROR VOLTAGE, and the error voltage in turn controls a magnetic amplifier. The POWER amplification occurs in the magnetic amplifier. The various ways that a magnetic amplifier does this are explained in chapter 18, Magnetic Amplifiers.

Regardless of the type of amplifier used, the output of the power amplifier is connected to the control field of the servomotor. In this illustration,. a single-phase induction motor is used. The fixed field is energized at all times but cannot turn the motor shaft unaided. The control field is energized only when an error voltage appears at the control transformer When the control field is energized, the motor operates.

The direction of rotation of the motor is determined by the phase relationship of the voltage applied to the fixed field to that of the control field. Varying phase relationships occur in the

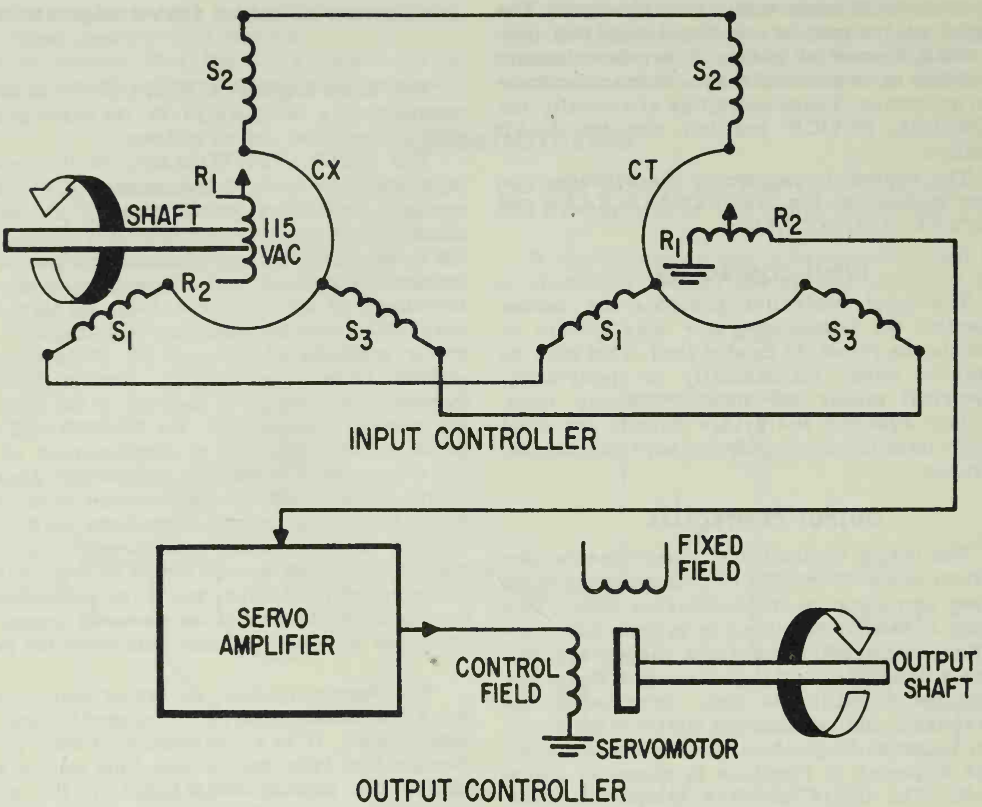

S2
S2
CX
CT
R1
R2
SHAFT
115
VAC
R2
R1
S1
S3
S1
S3
INPUT CONTROLLER
SERVO
AMPLIFIER
FIXED
FIELD
CONTROL
FIELD
OUTPUT
SHAFT
SERVOMOTOR
OUTPUT CONTROLLER

Figure 19-27.–Schematic diagram of figure 19-26.

control field only, because its voltage (magnitude and phase relationship) is determined by the direction of displacement of the control transmitter rotor.

Once the input controller in the system just discussed produces an error voltage, the servomotor continues to turn until the rotor of the control transmitter is again in its electrical zero (null) position. This is called an OPEN LOOP control system, because the servo output has no means of changing the input during operation.

Figure 19-28 shows the simplified block diagram of a servomechanism system that is much more widely used. It is the CLOSED-LOOP control system. Note that it is similar to the open-loop system, except that an additional function line extends from the servo to the amplifier input.

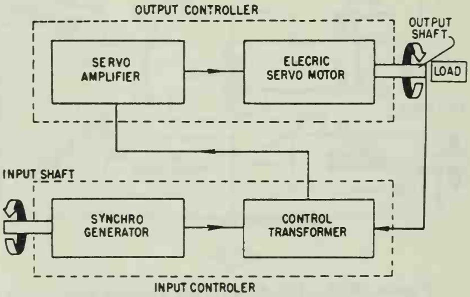

OUTPUT CONTROLLER
OUTPUT
SHAFT
SERVO
AMPLIFIER
ELECRIC
SERVO MOTOR
LOAD
INPUT SHAFT
SYNCHRO
GENERATOR
CONTROL
TRANSFORMER
INPUT CONTROLER

Figure 19-28.–Closed-loop servomechanism.

In the closed-loop control system, the servomotor can be made to stop at any position, without returning the rotor of the control transmitter to its electrical zero position. To accomplish this, an error voltage controlled by the servo is necessary. This error voltage is called a FOLLOWUP voltage.

To provide this followup voltage, there is usually a bridge element or a control transformer driven by the servo's output shaft. The electrical connection is such that the bridge or control transformer will generate a voltage opposing the error voltage of the input controller. Figure 19-29 shows a schematic diagram of the closed-loop control system.

The followup control transformer is basically the same in construction as those discussed earlier. Note that the stator is excited by the same a-c voltage as the rotor of the control transmitter. This voltage is connected only across two of the stator windings. The third stator winding is not used. With a voltage applied across the two windings 120 degrees apart, a resultant magnetic field appears midway (60°) between the two windings. If the rotor of the followup control transmitter is placed so that its axis is 90 degrees from the field axis, the voltage induced in the rotor from the two stator windings is zero. It can be seen that if the rotor is moved from this zero-voltage position, a

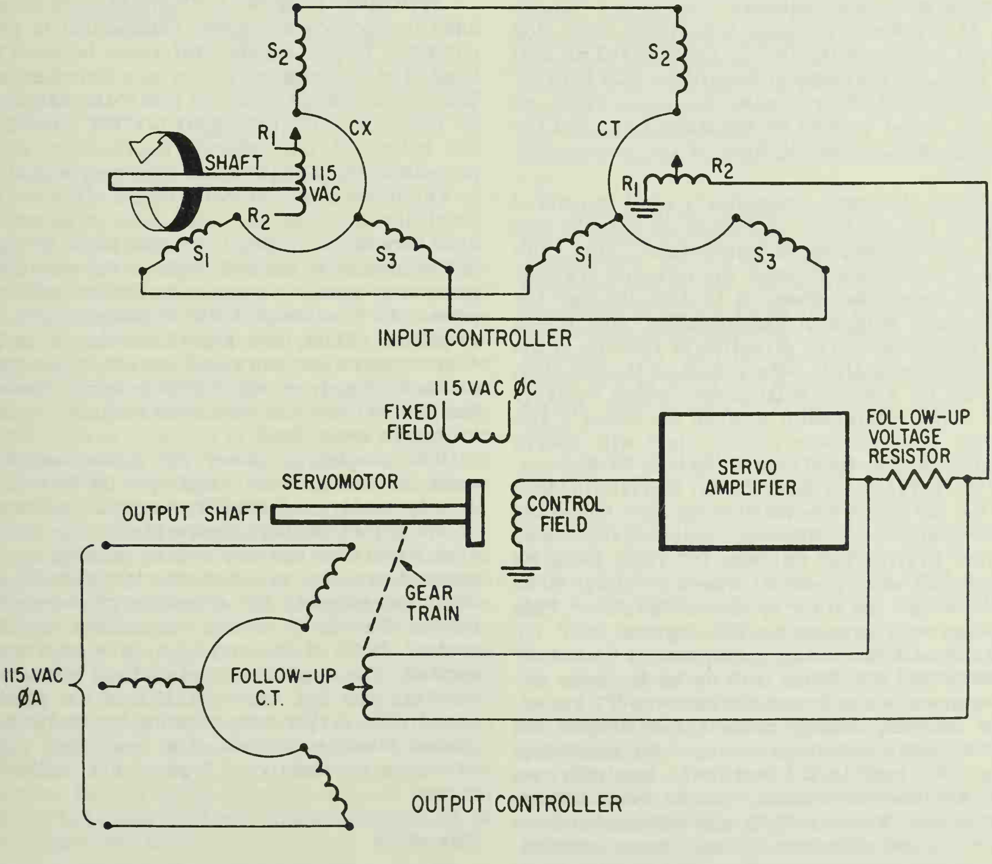

S2
S2
CX
CT
R1
SHAFT
115 VAC
R2
R1
R2
S1
S3
S1
S3
INPUT CONTROLLER
115 VAC ØC
FIXED FIELD
SERVOMOTOR
OUTPUT SHAFT
CONTROL FIELD
SERVO AMPLIFIER
FOLLOW-UP VOLTAGE RESISTOR
GEAR TRAIN
115 VAC ØA
FOLLOW-UP C.T.
OUTPUT CONTROLLER

Figure 19-29.—Closed-loop control system.

voltage will be induced into the rotor. The magnitude and phase-relationship of this voltage is dependent upon the amount of displacement, and the direction of rotation of the rotor from its zero position.

When a followup control transformer is used in a servomechanism system, as illustrated in figure 19-29, the rotor is usually driven through a gear train by the servomotor's output shaft. The gear ratio will be such that the output shaft will turn many times before the rotor is turned any appreciable amount. Ratios of 1,500 to 1 are common. The servomotor output shaft may either be connected directly to its load, or geared up or down.

The principle of operation of the closed-loop servosystem is as follows:

At the static position (electrical zero) the output voltage of the INPUT CONTROLLER will be zero, and the output voltage of the FOLLOWUP TRANSFORMER will also be zero. Thus, no error signal is sent to the amplifier, and the voltage to the control field of the servomotor is zero.

When the input controller's shaft is rotated (either left or right) a voltage is induced into the rotor of the control transformer. This voltage is connected through the followup resistor to the amplifier, where it is sent through the necessary stages of amplification, and drives the servomotor. The direction of rotation of the servomotor shaft is determined by the direction of the TX rotor displacement, which controls the phase relationship between the motor's two fields. The variable control field will always lead or lag the fixed control field by 90 degrees. As the servomotor shaft turns, it drives the load in the direction commanded. It also drives the gear train of the followup control transformer rotor. Driving the followup CT rotor from its electrical zero position causes a voltage to be induced into the rotor by the excited stator. This voltage will always be 180 degrees OUT OF PHASE with the voltage generated by the INPUT CONTROLLER. (This is done by the gear arrangement which drives the followup CT rotor). The followup voltage is developed across the same followup voltage resistor through which command signals are sent to the amplifier. As the servomotor rotates, the followup voltage increases. When the followup voltage becomes equal to the command voltage, being opposite, the error voltage sensed by the amplifier will be zero. The servomotor stops rotating. Note that it is unnecessary to reposition the control transmitter's rotor (input controller) to electrical zero in order to stop rotation of the servomotor. The servomotor will rotate to move the load to whatever position is commanded by the control transmitter.

AMPLIDYNES

As has been stated earlier in this chapter, SYNCHROS are used for the transmission of angular motion without developing a large amount of torque.

DIFFERENTIAL SYNCHROS are used for combining, in the desired manner angular motion from two different sources, again without developing a large amount of torque.

SYNCHRO CONTROL TRANSFORMERS are used to produce an output voltage that is proportional to the angular difference between the input and output shafts of a servomechanism. The error voltage from the control transformer is fed to a CONTROL AMPLIFIER (amplifies the output of the control transformer) which increases the amplitude of the error signal. In an amplidyne power drive the output of the control amplifier supplies the field coils of an amplidyne generator. A small variation in the strength of the current in the field coils of the amplidyne generator causes a great variation in its output power. In this respect the amplidyne is a d-c amplifier. Thus, the signal developed in the control amplifier can cause the amplidyne generator to supply enough output power to operate the d-c servomotor which has sufficient torque to move a heavy load.

The amplidyne power drive, as commonly used, consists of an amplidyne generator, a driving motor, and a d-c servomotor, as shown in simplified form in figure 19-30. The amplidyne generator has two sets of brushes on the commutator. One set is short-circuited and the other set supplies the armature of the servomotor. The field of the servomotor and the control field of the amplidyne are separately excited. The amplidyne control field has a split winding, one for each polarity of the applied signal. The series compensating winding is discussed later in the text. The amplidyne drive motor is ordinarily a 3-phase a-c induction motor.

Operation

The amplidyne generator is a small separately excited direct-current generator having a

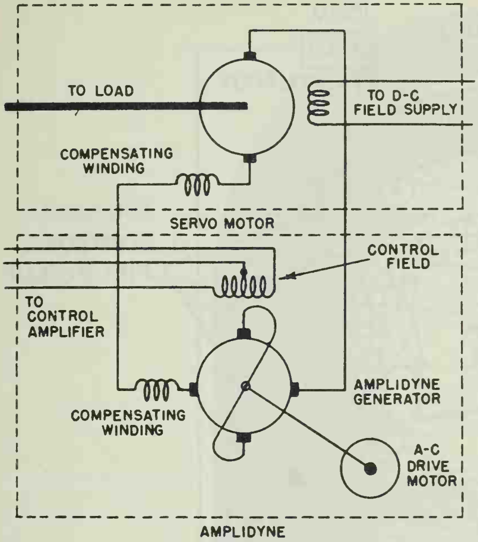


Figure 19-30.—Basic amplidyne drive.

control field that requires a low power input. The armature output voltage may be 100 volts and the output load current 100 amperes, giving an output power of 10 kilowatts (kw.). The amplidyne is essentially a control device that is extremely sensitive. For example, an increase in control field power from zero to 1 watt can cause the generator output power to increase from zero to 10 kw. It is thus a power amplifier that increases the power by an amplification factor of 10,000. The following analysis shows how this high amplification is accomplished.

In an ordinary 2-pole generator (fig. 19-31) the separately excited control field may take an input power of 100 watts in order to establish normal magnetism in the field poles and a normal armature voltage of 100 volts. When this voltage is impressed on a 1-ohm load the armature will deliver 100 amperes, or an output power of 10 kw. The circles with dots represent armature conductors carrying current toward the observer; those with crosses represent electron flow away from the observer. The control field winding develops a north pole (N) on the left-hand field pole and a south pole (S) on the right-hand field pole.

The relative strength of the control field is represented by vector OA in figure 19-31 (B). The armature acting as an electromagnet establishes a quadrature, or cross, magnetomotive force having an axis that coincides with that of the brushes. The relative strength and position of this armature cross magnetizing force is indicated by vector OB in figure 19-31 (B). It has about the same length as the control field vector, OA, and is perpendicular to it.

If the strength of the control field in figure 19-31 (A) is reduced to 1 percent of normal, the armature generated voltage will fall to 1 percent of normal, or to about 1 volt in this example. The output current from the armature will fall to 1 ampere through the 1-ohm load.

Normal armature current may be restored by short-circuiting the brushes, as shown in figure 19-32 (A). One volt acting through an internal armature resistance of 0.01 ohm will circulate 100 amperes between the brushes. The control field strength is still 1 percent of its normal value (vector OA, fig. 19-32 (B)), but the armature crossfield m.m.f. has been restored to its normal value, as indicated by vector OB.

The armature crossfield is cut by the armature conductors and may be regarded as being responsible for normal load voltage, which is obtained across an additional pair of brushes, as shown in figure 19-33 (A). The axis of these brushes is perpendicular to that of the shorted brushes. The load is connected in series with these new brushes and a compensating winding, shown schematically around the south field pole, S.

Armature load current is toward the observer around the upper half of the armature windings and away from the observer around the lower half. The armature acts like an electromagnet, which creates an m.m.f. directly opposed (in this case) to the control field m.m.f. and in the same axis as that of the control field.

The purpose of the compensating winding is to create an opposing m.m.f. along this same axis to counterbalance the armature load current m.m.f. This counterbalance is made automatic for any degree of load by connecting the compensating winding in series with the load brushes and the load. Vector OC (fig. 19-33 (B)) represents the relative magnitude and direction of the compensating winding m.m.f. with respect to the control field m.m.f. OA; the armature load current m.m.f. OD; and the armature crossfield m.m.f. OB.

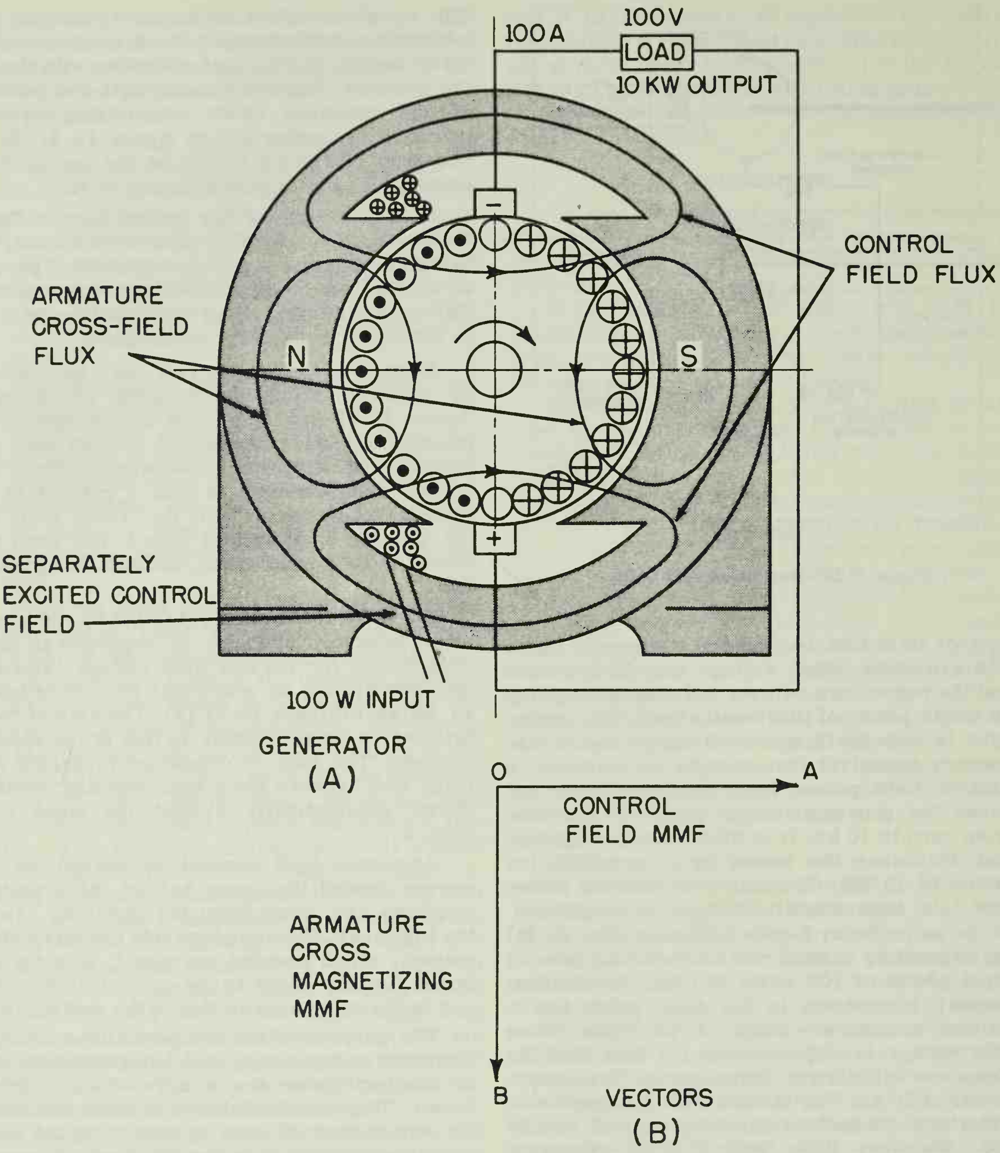

100 A
100 V
LOAD
10 KW OUTPUT
CONTROL FIELD FLUX
ARMATURE CROSS-FIELD FLUX
N
S
−
+
SEPARATELY EXCITED CONTROL FIELD
100 W INPUT
GENERATOR
(A)
O
A
CONTROL FIELD MMF
ARMATURE CROSS MAGNETIZING MMF
B
VECTORS
(B)

Figure 19-31.—Ordinary d-c generator.

The main field poles are shown slotted along the load-brush (horizontal) axis to indicate a method of achieving satisfactory commutation in the coils being shorted by these brushes. A restriction in the size of the amplidyne is the self-induced voltage in the coils being commutated and the resultant sparking at the commutator.

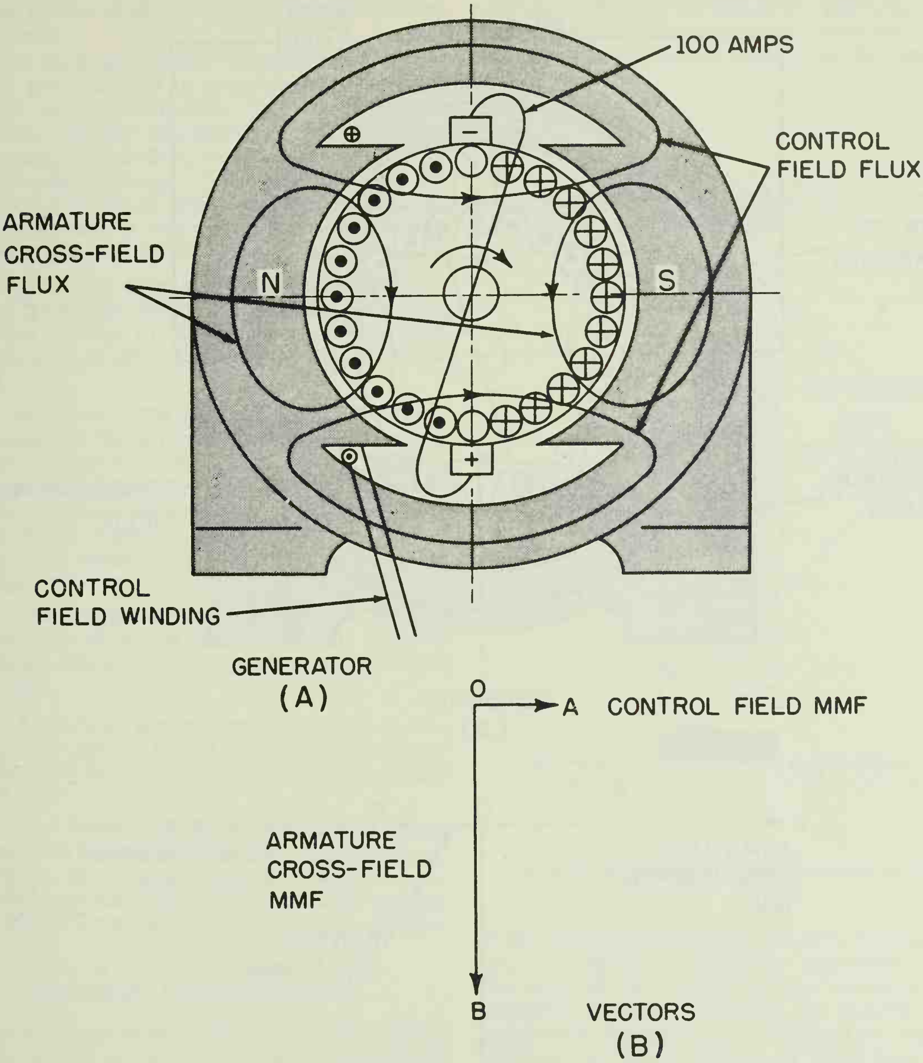

100 AMPS
CONTROL FIELD FLUX
ARMATURE CROSS-FIELD FLUX
−
N
S
+
CONTROL FIELD WINDING
GENERATOR
(A)
O
A
CONTROL FIELD MMF
ARMATURE CROSS-FIELD MMF
B
VECTORS
(B)

Figure 19-32.—Generator with short-circuited brushes.

Because any residual magnetism along the axis of the control field would have an appreciable effect on the amplidyne output, it is necessary to demagnetize the core material when the control field winding is deenergized. This demagnetization is accomplished by means of a small a-c magneto generator (mounted on the amplidyne frame) which supplies a suitably placed demagnetizing winding, known as a KILLER WINDING (fig. 19-33 (A)).

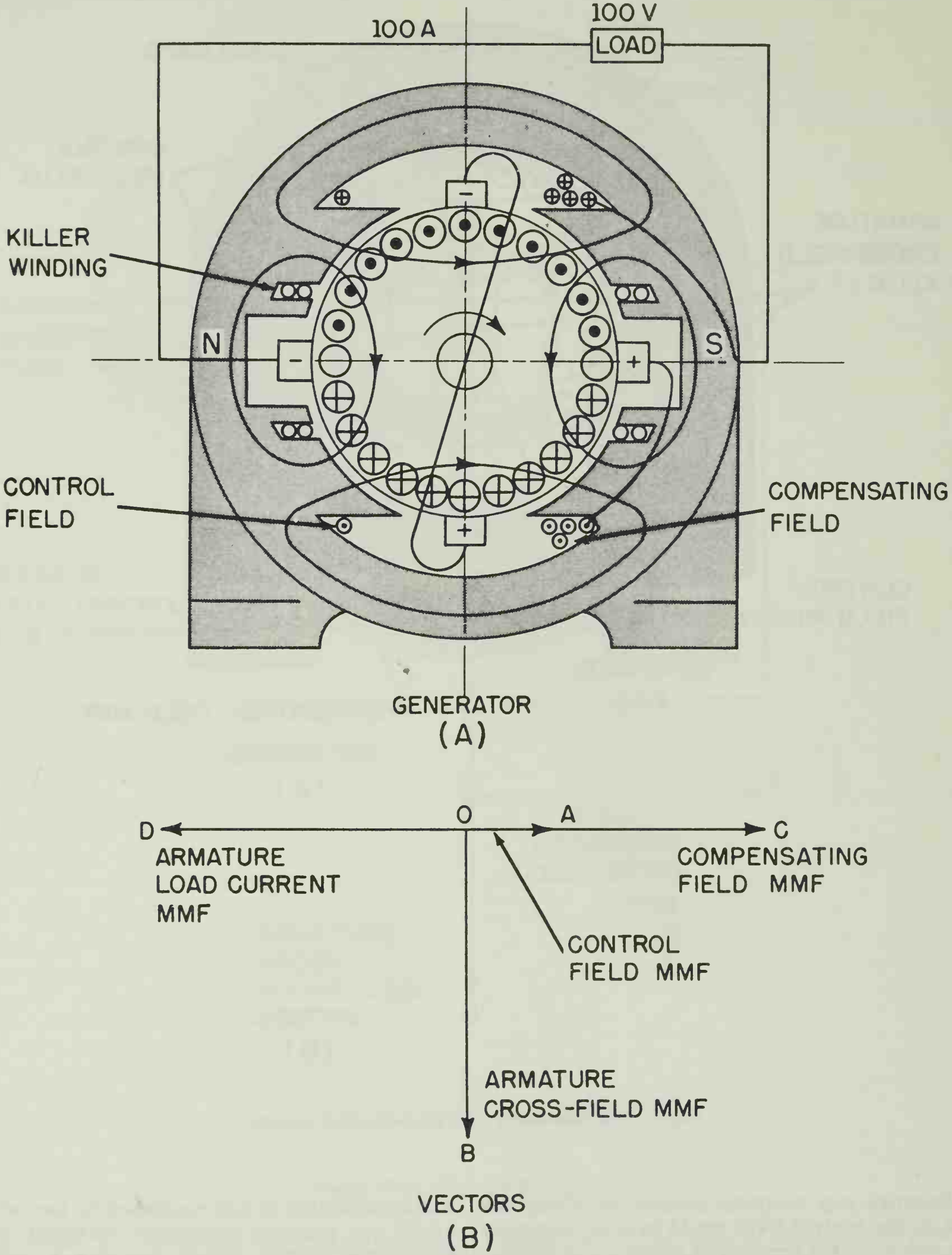

100 A
100 V
LOAD
KILLER WINDING
N
S
CONTROL FIELD
COMPENSATING FIELD
GENERATOR
(A)
D
O
A
C
ARMATURE LOAD CURRENT MMF
COMPENSATING FIELD MMF
CONTROL FIELD MMF
ARMATURE CROSS-FIELD MMF
B
VECTORS
(B)

Figure 19-33.—Amplidyne generator.

The action of the amplidyne is summarized as follows:

1. A very low power (1 watt) input to the control field creates an armature short-circuit current of 100 amperes, thus producing a relatively strong armature crossfield. This is responsible, in turn, for the generation of a normal output voltage of 100 volts across the output load brushes. The output load of 1 ohm is supplied with a current of 100 amperes and an output power of 10,000 watts.

2. In larger size amplidyne generators, a control field input power of 4 watts will develop an output voltage of 200 volts and an armature load current of 200 amperes, or 40,000 watts output.

3. Because of the high power amplification, any residual magnetism in the poles would greatly interfere with the proportion between the input and output. Residual magnetism is removed by means of a small a-c magneto generator which supplies a demagnetizing winding having the same axis as the control field winding.

4. The laminated armature and stator cores are worked at a low flux density in order to maintain a straight-line proportion between input and output.

5. Amplidyne generators are driven at relatively high speeds (1,800 r.p.m. to 4,000 r.p.m.) in order that they may be of small size and light weight.

6. The amplidyne generator has a quick response to changes in control field current. The lapse in time between a change in the magnitude of the control field current and the load output response is about 0.1 second.

ANTIHUNT CONSIDERATIONS

One problem in the application of the servosystem is that of hunting. Hunting refers to the tendency of a mechanical system to oscillate about a normal position. Thus, in figure 19-34 the steel ball, if depressed from its normal position and suddenly released, oscillates vertically because of its inertia and the forces exerted by the springs. In time, the oscillation is damped out by the frictional losses in the oscillating system.

Although other factors are involved, a somewhat similar effect is observed in radar fire control, and other equipments employing servo drive. Because the connection between the handwheel or other device controlling the position of the equipment (antenna, gun, etc., to be moved) and the equipment itself is somewhat elastic (because of the action of the electrical and magnetic circuits involved), the inertia of the equipment causes it to overtravel its required position. An error voltage is developed in the servosystem in the opposite direction and the equipment reverses. Successive overtravels by the equipment would be less and less, and the mechanical oscillation would die out except for one factor: there may be a time lag in the servosystem, which causes reinforced oscillations. In such a case, the equipment would continue to oscillate or HUNT about its normal position. This action would cause harmful mechanical vibration of the entire rotating system.

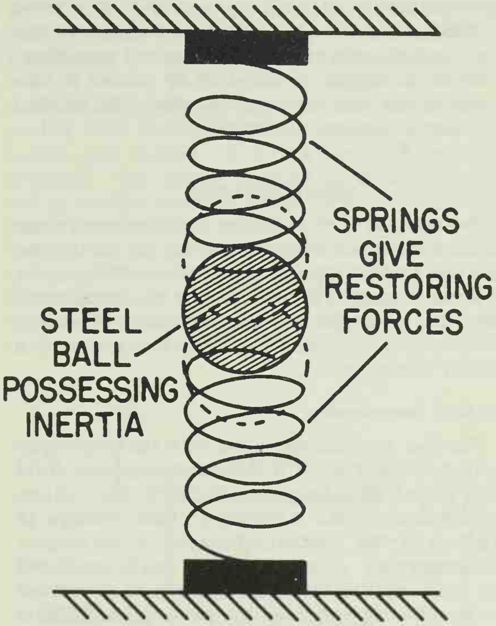


Figure 19-34.—Mechanical demonstration of hunting.

In order to eliminate hunting, an ANTIHUNT device or circuit is used. This device commonly consists of arrangements to slow up the drive motor as the equipment to be moved approaches its final position. If the drive power is reduced soon enough, the inertia of the moving part causes it to coast into its final position without any overtravel.

The antihunt circuit commonly connects the servo or followup motor to the control amplifier. A feedback signal is supplied by means of this circuit to the control amplifier where the hunting problem is handled electrically.

SERVOMOTORS

The output drive motor in a servosystem should have the required power, be easily reversible, and be capable of speed control over a fairly wide range. The d-c motor has characteristics that make its use advantageous. However, under certain circumstances the a-c motor has distinct advantages.

The D-C Servomotor

The d-c servomotor used with the amplidyne generator must have a constant magnetic field if its output is to be proportional to the voltage applied across its armature. This voltage is supplied by the controlled output of the amplidyne generator. A constant field can be produced by a field winding supplied by a constant-voltage d-c source, or supplied by means of a suitable rectifier and an a-c source. A simpler method is to use permanent magnets that are capable of establishing the necessary flux. These are restricted to small-size, low-horsepower motors.

A disadvantage in using permanent magnets is that they may become demagnetized by armature reaction. However, this condition may be counteracted by the use of a compensating winding. This winding is connected in series with the armature and so placed around the pole faces that the armature reaction effect is completely eliminated.

The A-C Servomotor

As has been stated, the output drive motor in a servosystem should be easily reversible and should be capable of speed control over a fairly wide range. Ordinarily, an a-c motor cannot fulfill the requirements of a servo drive motor as completely as a d-c motor because the range of speed control is less. However, the use of an a-c motor may provide a much simpler drive system, especially where a-c power is the only source available and where some sacrifice in range of speed control can be made.

An a-c motor that can be adapted for servosystem use is the single-phase induction motor. This motor contains two stator windings. They are the starting and running windings and are displaced 90 degrees. Their currents are displaced in time phase to produce a revolving magnetic field. The rotor may be either a WOUND rotor or a CAGE rotor. The latter type is the most common. It consists of heavy conducting bars embedded in the armature slots and connected at the ends by conducting rings. The revolving magnetic field originating in the stator cuts the rotor windings when power is applied at start and induces voltages in them. The resulting rotor currents react with the field to start the motor in the direction of the revolving field.

The starting winding is frequently designed to operate continuously with a capacitor to increase the phase displacement between the currents at start and to improve the motor power factor when the motor comes up to speed. When this arrangement is used it is called a CAPACITOR MOTOR. In order to reduce the size of the phase-splitting capacitor required for induction motor applications (and to produce essentially the same result), a high voltage capacitor of smaller capacitance and a small autotransformer are used. The operation of the capacitor motor and the method of employing the capacitor are explained in chapter 13.

In order to give the necessary range of speed control and higher starting torque for certain applications, it is possible to modify the two-phase motor in other ways. These include increasing the resistance of the rotor bars and end rings and the use of a tapped autotransformer, one arrangement of which is shown in figure 19-35. In this circuit the phase-splitting capacitor and autotransformer are placed in parallel with one coil, and the combination is placed in series with the second coil. The current through coil 1 is the vector sum of the lagging current through coil 2 and the leading current through the primary of the autotransformer. Because the current through the capacitor is leading the current through coil 2, the total current through coil 1 leads that through coil 2. The capacitor is chosen to give approximately a 90-degree phase shift between the currents in coils 1 and 2. Thus, the desired rotating magnetic field is produced. However, the efficiency of this type of motor is relatively poor because of the high resistance rotor.

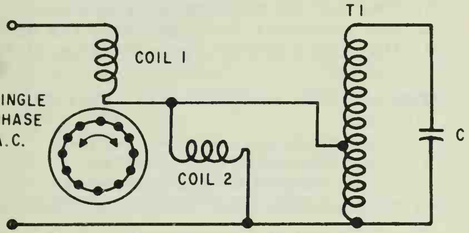


Figure 19-35.—Single-phase capacitor motor with series stator coil connections.

The DIRECTION of rotation of the capacitor motor is reversed either by reversing the connections to one stator coil or by shifting the capacitor from one coil to the other. The SPEED of the motor is varied over a limited range by changing the voltage applied to the motor. The voltage may be changed by placing a variable impedance in series with one or both phases. The effect of such an impedance is to lower the voltage, and hence the current, input to the windings. This action weakens the field and lowers the induced voltage in the rotor bars, hence reduces the motor torque and speed. The basic requirements of this system are: (1) a means of using an error signal to vary the impedance in series with the motor in order to control the speed, and (2) a means of comparing the phase of the error signal with a reference voltage in order to control the direction of rotation of the motor.

The block diagram of a servosystem in which a capacitor motor is used to provide the output power is shown in figure 19-36. A synchro control transformer is used to provide an error signal that is proportional to the difference between the actual antenna position and the desired position, represented by the position of the handwheel. The rotor of the control transformer is geared to the load so that rotation of the load turns the rotor toward the position in which the error voltage is zero. The antenna is rotated by turning the handwheel connected to the rotor of the synchro transmitter. The turning of the rotor shifts the position of the stator field of the control transformer and thus causes an error voltage to be induced in its rotor. The error voltage is fed to the control amplifier where it is amplified and used to lower the impedance in series with the a-c motor in order to start the motor, and to control (within limits) the speed of rotation. The error voltage is simultaneously fed to another section of the amplifier where its phase is compared with the phase of a reference voltage in order to control the direction of rotation. The output of this section of the amplifier is fed to a relay which selects the stator winding with which the phase-splitting capacitor is to be connected in series.

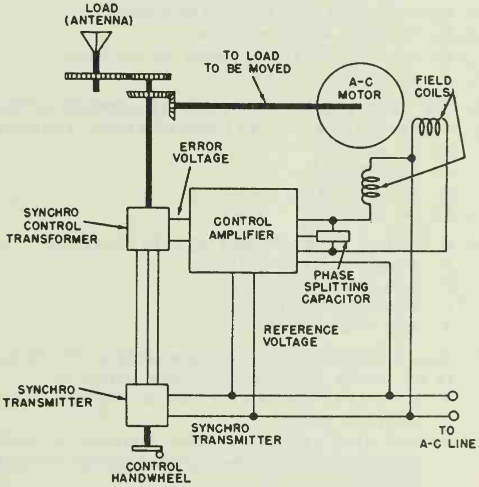


Figure 19-36.—Servosystem using capacitor motor.

QUIZ

1. The direction of rotation of a capacitor motor can be reversed by
   a. reversing connections to the noncapacitor phase
   b. reversing connection to the capacitor phase
   c. reversing source power connections
   d. shifting the capacitor from one phase to the other
2. A synchro transmitter is connected to a synchro motor
   a. mechanically
   b. magnetically
   c. directly
   d. electrically
3. If S2 and either S1 or S3 are reversed at the receiver, the rotor will
   a. reverse direction with no error
   b. be 180° in error
   c. be 120° in error
   d. not be affected
4. A basic synchro system is used to
   a. transmit position information
   b. control drive motors
   c. control large amounts of current
   d. transfer energy
5. To reverse the direction of rotation of the rotor of the receiver (with no error) reverse
   a. S1 and S2
   b. R1 and R2
   c. S2 and S3
   d. S1 and S3
6. A control transformer synchro uses a
   a. squirrel cage rotor
   b. drum wound rotor
   c. salient pole rotor
   d. lap wound rotor
7. The purpose of the compensating windings is to create a magnetomotive force to
   a. counterbalance the armature load current m.m.f.
   b. aid the armature load current m.m.f.
   c. counterbalance the control field current m.m.f.
   d. aid the control field current m.m.f.
8. The a-c servomotor is a
   a. 3Φ induction motor
   b. 1Φ repulsion induction motor
   c. 1Φ induction motor
   d. 1Φ series motor
9. A synchro is comparable to a
   a. single-phase transformer
   b. generator
   c. synchronous motor
   d. three-phase transformer
10. Synchro generators and motors are usually not interchangeable because
    a. they are not electrically identical
    b. they are not mechanically identical
    c. the generator is larger than the motor
    d. the generator operates at a higher voltage
11. The essential components of a servomechanism are
    a. input controller and transmitter
    b. input controller and receiver
    c. output controller and transmitter
    d. output controller and input controller
12. The differential synchro transmitter uses a rotor having
    a. a single coil
    b. three separately connected coils
    c. three wye-connected coils
    d. three delta-connected coils
13. With both rotors in the same position and maximum voltage induced in winding S2, there is
    a. minimum current flow in the system
    b. maximum current flow in the system
    c. minimum current flow in stator windings
    d. maximum current flow in stator windings
14. Driving the followup center tap rotor from the electrical zero position causes a voltage to be induced into the rotor by the excited stator. This voltage will be
    a. in phase with the voltage generated by the input controller
    b. out of phase with the voltage generated by the output controller
    c. in phase with the voltage generated by the output controller
    d. out of phase with the voltage generated by the input controller
15. The generator and motor rotors are connected
    a. in parallel
    b. in series
    c. to separate sources
    d. by mutual inductance
16. The stator voltages are
    a. in phase and subtractive
    b. out of phase and subtractive
    c. in phase and additive
    d. out of phase and additive
17. The motor rotor will follow the generator rotor because of
    a. magnetic coupling
    b. induced e.m.f.
    c. c.e.m.f.
    d. generator movement

18. The windings of the synchro stators are displaced from each other by
    - a. 45°
    - b. 90°
    - c. 120°
    - d. 240°
19. An amplidyne is a/an
    - a. a-c amplifier
    - b. d-c amplifier
    - c. ac-dc amplifier
    - d. d-c servomotor
20. The rotor of a synchro must continuously draw current to
    - a. produce heat
    - b. maintain a magnetized rotor
    - c. set up a reference voltage
    - d. produce an induced voltage in the stator
21. Synchro systems will be at a null when induced e.m.f.'s are
    - a. in phase and equal
    - b. out of phase and equal
    - c. in phase and not equal
    - d. out of phase and not equal
22. The amplidyne drive motor is usually a
    - a. d-c compound motor
    - b. d-c series motor
    - c. one-phase a-c induction motor
    - d. three-phase a-c induction motor

CHAPTER 20

ELECTRICAL DRAWINGS AND TECHNICAL MANUALS

This course has presented the basic principles of electricity. These principles are widely applicable. For instance, the laws of voltage distribution around a closed circuit apply equally to a-c and d-c circuits irrespective of the number of voltage sources or the nature of the components of the circuit. When analyzing the operation of even the most complex circuit or equipment, the principles of its functions may be explained by one or more of the widely applicable electrical laws. Thus, the first step in your technical training is learning these laws, most of which are set forth in the preceding parts of this text. The second step, gained largely through experience, is learning the methods and practices by which these principles are put to work, in the form of actual hardware, in hundreds of different types of equipment.

One of the best ways to learn these methods and common practices is to become familiar with the language of practical electricity. This language is found in the technical manual (instruction book) written for each equipment and in the diagrams for each system. You cannot hope to memorize every detail of every circuit in the complex systems and equipments you must maintain. A good technician does not even attempt it. Instead, you should be able to obtain this information as you need it from the manuals and drawings provided for that purpose. To do this, you must be able to read electrical drawings and diagrams. The ability to read a particular drawing, coupled with the basic principles of electricity, will make it much easier for you to understand, adjust, operate, and repair any particular equipment or circuit.

In the construction of a wiring or schematic diagram of a circuit or system, it would not be practical, and rarely even useful, to draw pictures of each part as they actually appear. Instead, each part in a wiring or schematic diagram is represented by a symbol. Electrical symbols are to the technician as shorthand is to the stenographer. All parts, such as resistors, capacitors, switches, relays, and so forth, have symbols that are standard Navy-wide. The most important ability in reading electrical drawings is the ability of the technician to form a mental correlation between the symbol for a part as it appears in a diagram, and the actual appearance and function of that part.

Electrical Symbols

Table 20-1 is a listing of some of the most common standard electrical parts. The name and standard symbol for each part are given, along with a picture. By studying this list, and others similar to it, you will be able to mentally correlate parts and their symbols, which is necessary in developing the ability to read electrical diagrams.

A brief discussion of some of the most common parts that are used in electrical circuits follows the list of symbols.

RESISTOR COLOR CODING

As you probably know, a resistor is a device used to limit current flow. Resistors are of two types: fixed and variable. Fixed resistors may be made of wire wound on a core and coated with ceramic or they may be made of carbon. The majority of fixed resistors have axial leads. Resistance value is indicated by 3 colored bands. A fourth band is sometimes used to indicate tolerance as follows: gold = ±5 percent, silver = ±10 percent. When no fourth band is present,

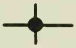
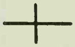
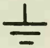
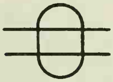
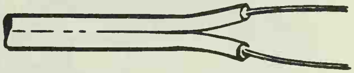
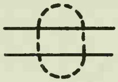
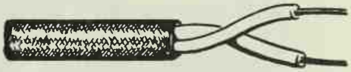
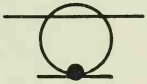
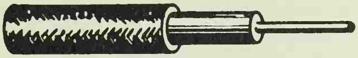
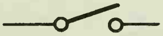
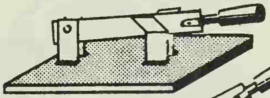
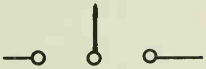
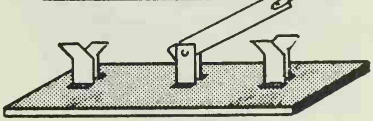
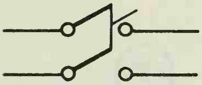
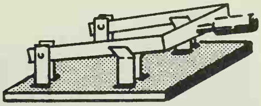
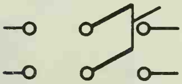
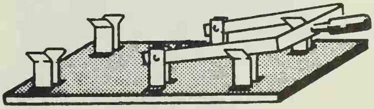
Name	Symbol	Picture
CONNECTION		
NO CONNECTION		
GROUND		
TWO-CONDUCTOR CABLE		
SHIELDED TWO-CONDUCTOR CABLE		
COAXIAL CABLE		
SINGLE POLE SINGLE THROW SWITCH		
SINGLE POLE DOUBLE THROW SWITCH		
DOUBLE POLE SINGLE THROW SWITCH		
DOUBLE POLE DOUBLE THROW SWITCH		

Table 20-1. — Electrical symbols.

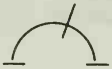
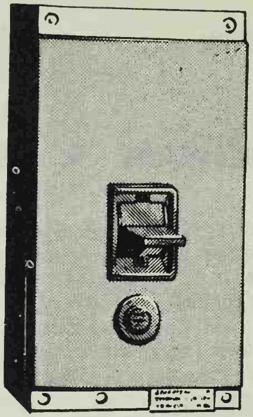
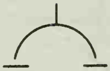
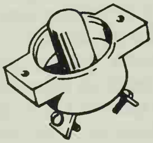
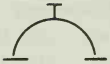
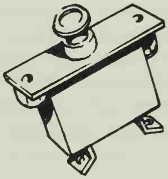
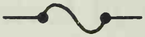
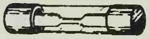
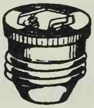
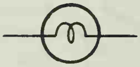
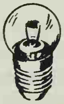
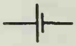
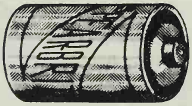
Name	Symbol	Picture
SWITCH CIRCUIT BREAKER		
PUSH CIRCUIT BREAKER		
PUSH-PULL CIRCUIT BREAKER		
FUSE		 
LAMP		
CELL (LONG VERTICAL LINE IS ALWAYS POSITIVE)		

Table 20-1. — Electrical symbols — Continued

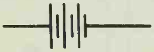
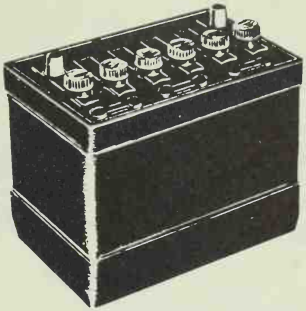
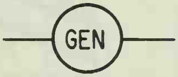
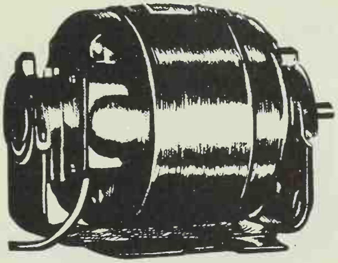
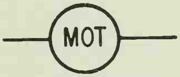
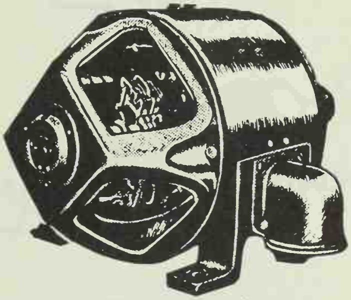
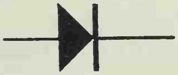
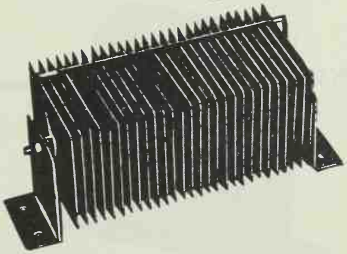
Name	Symbol	Picture
BATTERY		
GENERATOR (MAY BE A-C OR D-C, DEPENDING ON HOW LABELED)		
MOTOR (MAY BE A-C OR D-C DEPENDING ON HOW LABELED)		
METALLIC RECTIFIER		

Table 20-1. – Electrical symbols – Continued

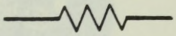
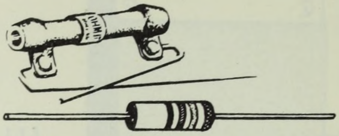
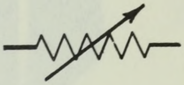
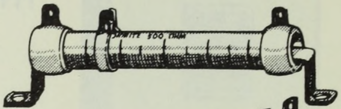
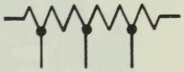
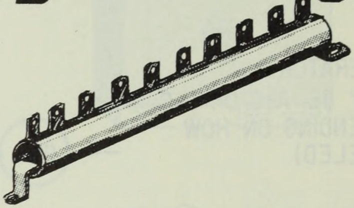
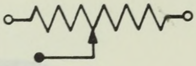
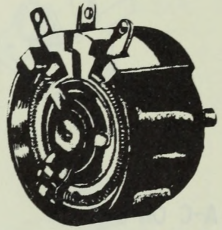
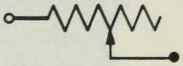
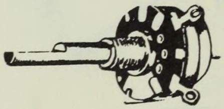
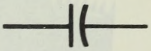
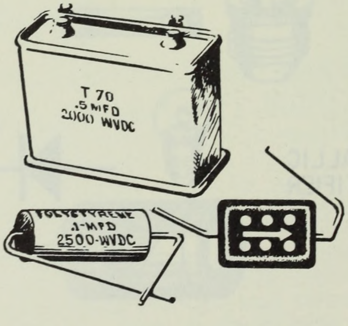
Name	Symbol	Picture
RESISTOR		
VARIABLE RESISTOR		
TAPPED RESISTOR		
POTENTIOMETER		
RHEOSTAT		
CAPACITOR, FIXED		

Table 20-1. – Electrical symbols – Continued

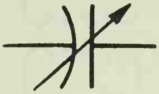
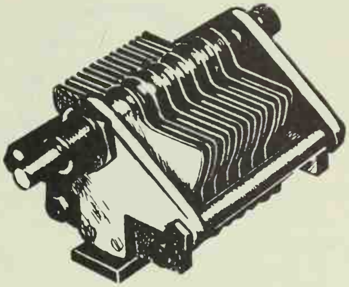
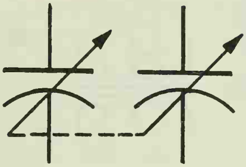
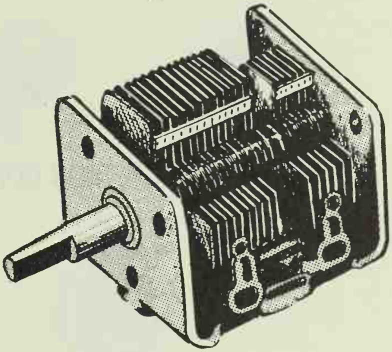
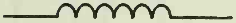
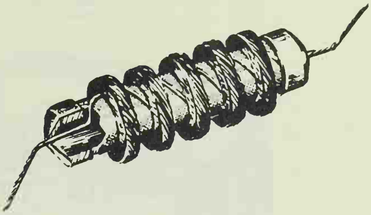
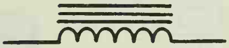
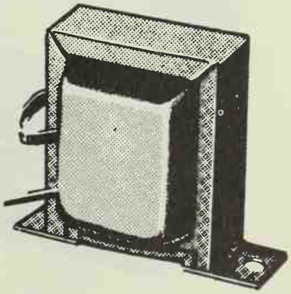
Name	Symbol	Picture
CAPACITOR, VARIABLE		
CAPACITOR, GANGED		
INDUCTOR, AIR CORE		
INDUCTOR, IRON CORE		

Table 20-1. — Electrical symbols — Continued

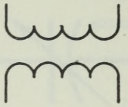
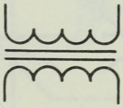
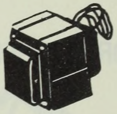
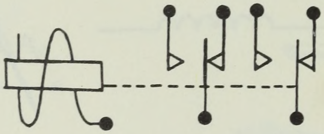
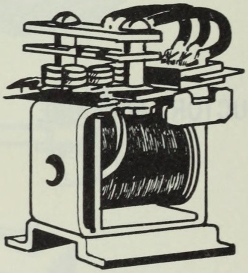
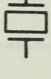
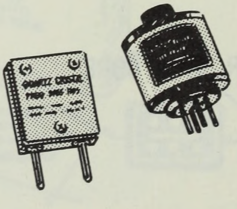
Name	Symbol	Picture
TRANSFORMER, AIR CORE		
TRANSFORMER, IRON CORE		
RELAY COIL WITH CONTACTS		
PIEZOELECTRIC CRYSTAL UNIT		

Table 20-1. – Electrical symbols – Continued

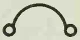
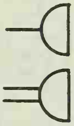
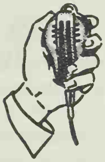
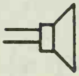
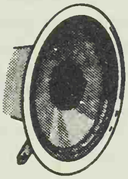
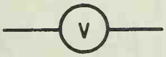
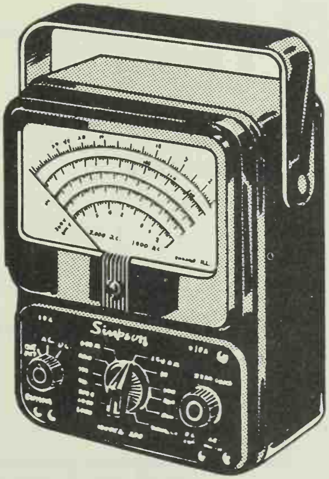
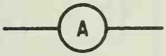
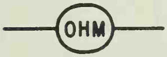
Name	Symbol	Picture
HEADPHONES		
MICROPHONE		
LOUDSPEAKER		
VOLTMETER		
AMMETER		
OHMMETER		

Table 20-1. — Electrical symbols — Continued

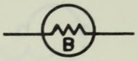
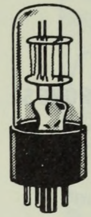
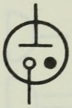
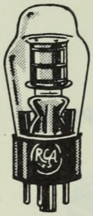
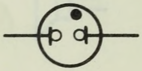
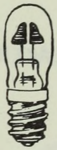
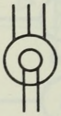
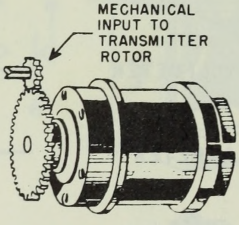
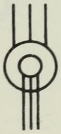
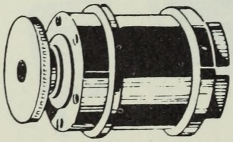
Name	Symbol	Picture
THERMAL RESISTOR (BALLAST LAMP)		
VOLTAGE REGULATOR OR GLOW TUBE (d-c TYPE)		
GLOW LAMP(COLD CATHODE) a-c TYPE		
SYNCHRO TRANSMITTER RECEIVER OR CONTROL TRANSFORMER		 MECHANICAL INPUT TO TRANSMITTER ROTOR
DIFFERENTIAL TRANSMITTER OR RECEIVER		

Table 20-1. – Electrical symbols – Continued

the resistor has a ±20 percent tolerance. For example, colored bands of red, orange, blue, and gold would indicate that the value of the resistor was 23 megohms (23,000,000 ohms) with a resistance tolerance of ±5 percent. (See fig. 20-1 and table 20-2.)

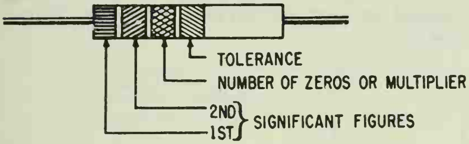
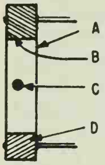


Figure 20-1.—Standard resistor coding.

Some fixed resistors are constructed with radial leads as shown in figure 20-2. The method of interpreting the color code to determine the value of these resistors is somewhat different from the method used with axial-lead resistors. (See fig. 20-2.) For example, if the body of the resistor is brown, end B is green, and dot C is yellow, the resistor will have a resistance of 150,000 ohms with a tolerance of 20% (no band D indicated).



COLOR

Body A	Indicates first significant figure of resistance value in ohms.
End B	Indicates second significant figure.
C (dot or band)	Indicates multiplier.
Band D	If any, indicates tolerance in percent. If no color appears in this position, tolerance is 20%.

Figure 20-2.—Color coding for radial-lead resistors.

Variable resistors are of two general types: rheostats and potentiometers.

A rheostat is a variable resistor which is normally used to adjust the current in a circuit without opening the circuit; however, some rheostats are constructed so that the circuit may also be opened. Generally, a rheostat has two terminals; one terminal is connected to one end of the resistance element, and the other terminal to the sliding contact. (See fig. 20-3.) As shown in this figure, the resistance element is circular in shape and is made of resistance wire wound around an insulating form usually made of a ceramic material. The resistance is decreased by rotating the wiper toward the end contact.

The potentiometer (often called a "pot") is a control device used to vary the amount of voltage applied to an electrical device. The term

Color	Significant figure or number of zeros	Decimal multiplier	Resistance tolerance
			Percent ±
BLACK	0	- - -	- - -
BROWN	1	- - -	- - -
RED	2	- - -	- - -
ORANGE	3	- - -	- - -
YELLOW	4	- - -	- - -
GREEN	5	- - -	- - -
BLUE	6	- - -	- - -
VIOLET	7	- - -	- - -
GRAY	8	- - -	- - -
WHITE	9	- - -	- - -
GOLD	- - -	0.1	5(J)*
SILVER	- - -	0.01	10(K)*
NO COLOR	- - -	- - -	20(M)*

* SYMBOL DESIGNATION ALTERNATE FOR COLOR

Table 20-2. — Standard color code for resistors.

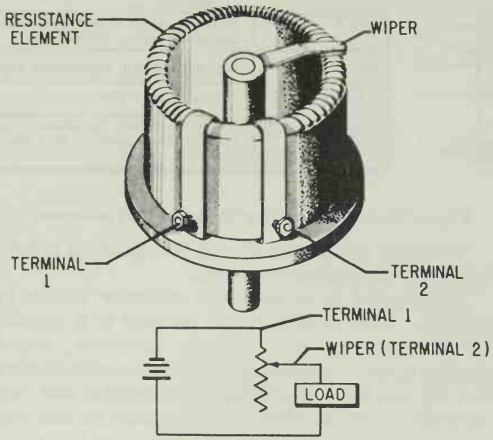


Figure 20-3.—Rheostat.

potentiometer is usually used to refer to any adjustable resistor having three terminals, two of which are connected to the ends of the resistance element and the third to the wiper contact. (See fig. 20-4.) By positioning the sliding contact, any desired voltage within the range of the potentiometer may be "picked off" and used where needed. As a rule, potentiometers are constructed to carry smaller currents than rheostats.

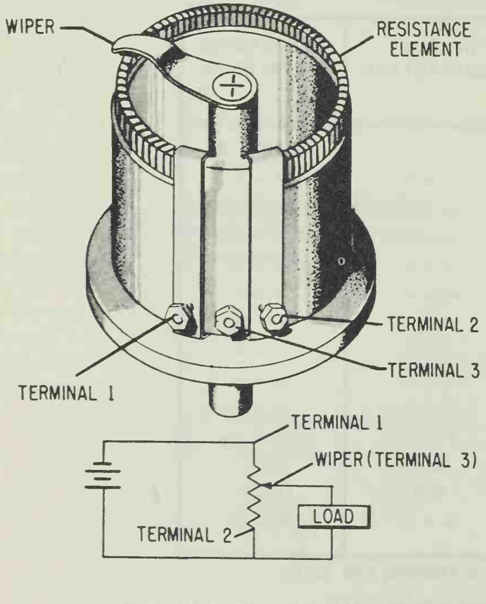


Figure 20-4.—Potentiometer.

Resistors are rated according to the heat they will safely dissipate. Heat is produced by current flow through a resistance; and as current increases, the temperature will rise. The watt is a unit of power and it represents the power expended in heat as current flows through the resistor:

$$P = I^2R$$

where P is the number of watts; I, the current flow through the resistor; and R, the resistance of the resistor.

The wattage rating of resistors is dependent on both the composition of the resistor and the physical size; as resistor size increases, wattage rating increases. Resistors used in Navy equipment usually have a wattage rating of at least 50 percent above the wattage that can be expected to be developed across them. For example, 5 watts would be developed across a 5-megohm resistor if 1 milliampere of current flowed through it.

$$P = I^2R$$

$$P = (1 \times 10^{-3})^2 \times 5 \times 10^6$$

$$P = 1 \times 10^{-6} \times 5 \times 10^6 = 5 \text{ watts}$$

Thus, this resistor should have a wattage rating of at least 7.5 watts.

Carbon resistors generally have a wattage rating of one-half to two watts. For wattage ratings of more than two watts, wire-wound resistors are generally used.

CAPACITOR COLOR CODING

The various types of capacitors were described in chapter 9 of this training course. Many capacitors are stamped with their working voltage and their value of capacitance. The capacitance is given in microfarads. (See fig. 20-5.) When the value of capacitance is not stamped on capacitors, it is indicated by the use of a color code as shown in table 20-3. On molded capacitors, colors are applied in the form of dots, four different marking systems being

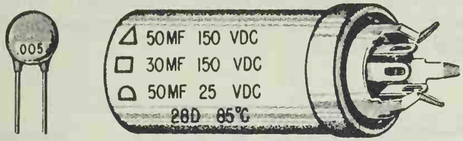

.005
50MF 150 VDC
30MF 150 VDC
50MF 25 VDC
28D 85°C

Figure 20.5.–Capacitors stamped with value of capacitance.

	Capacitance		
Color	Significant figure	Multiplier	Tolerance
BLACK	0	1	20%
BROWN	1	10	1%
RED	2	100	2%
ORANGE	3	1,000	3%
YELLOW	4	10,000	4%
GREEN	5	100,000	5%
BLUE	6	1,000,000	6%
VIOLET	7	10,000,000	7%
GRAY	8	100,000,000	8%
WHITE	9	1,000,000,000	9%
GOLD	- - -	0.1	5%
SILVER	- - -	0.01	10%

Table 20-3. – Color code for molded capacitors.

used to indicate the value of capacitance in micromicrofarads.

To read the three-dot system correctly, the capacitor must be held so that the arrows point to the right. The first and second dots indicate the first and second significant figures, respectively, and the third dot indicates the multiplier. (See fig. 20-6 (A).) For example, if the three colors were red, green, and orange, the value of the capacitor would be 25,000 micromicrofarads or 0.025 microfarads.

The five-dot system is interpreted by holding the capacitor so that three dots are in the top row and two dots in the bottom row. The three dots in the top row indicate the first three significant figures. The lower left dot in the bottom row is the multiplier, and the lower right dot is the tolerance. (See fig. 20-6 (B).)

The value of a capacitor coded with the six-dot system can be found by holding the capacitor so that the dot arrows point to the right. As shown in figure 20-6 (C), the three dots indicate the first, second, and third significant figures. The lower right dot specifies the multiplier; the lower middle dot, the tolerance; and the lower left dot, the voltage rating in hundreds of volts. This is the most frequently used color coding system. Assuming the top row of dots, reading from left to right, to be brown, red, and orange, and the bottom row, again reading from left to right, to be blue, green, and red, the capacitance would be 12,300 micromicrofarads; the voltage rating, 600 volts; and the tolerance, 5 percent.

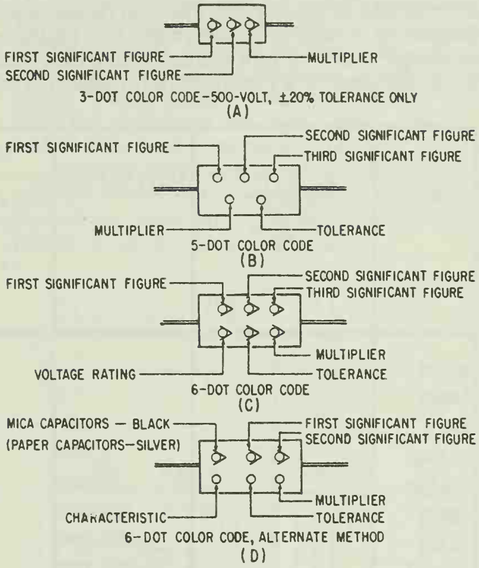

FIRST SIGNIFICANT FIGURE
SECOND SIGNIFICANT FIGURE
MULTIPLIER
3-DOT COLOR CODE-500-VOLT, ±20% TOLERANCE ONLY
(A)
FIRST SIGNIFICANT FIGURE
SECOND SIGNIFICANT FIGURE
THIRD SIGNIFICANT FIGURE
MULTIPLIER
TOLERANCE
5-DOT COLOR CODE
(B)
FIRST SIGNIFICANT FIGURE
SECOND SIGNIFICANT FIGURE
THIRD SIGNIFICANT FIGURE
MULTIPLIER
VOLTAGE RATING
TOLERANCE
6-DOT COLOR CODE
(C)
MICA CAPACITORS – BLACK
(PAPER CAPACITORS–SILVER)
FIRST SIGNIFICANT FIGURE
SECOND SIGNIFICANT FIGURE
MULTIPLIER
CHARACTERISTIC
TOLERANCE
6-DOT COLOR CODE, ALTERNATE METHOD
(D)

Figure 20-6.–Capacitor color coding. (A) Three-dot color code; (B) five-dot color code; (C) six-dot color code; (D) six-dot color code, alternate method.

The fourth color coding system also uses six dots, arranged in two rows, and again the capacitor must be held so that the arrows point to the right. However, in this system, the top left dot is either black, signifying a mica capacitor; or silver, signifying a paper capacitor. The second and third dots in the top row indicate the first two significant figures; the lower right dot, the multiplier, the lower center dot, the tolerance; and the lower left, the characteristics. "Characteristics" refer to such factors as the type case, dielectric, and temperature coefficient. (Temperature coefficient is the change in capacitance which occurs when a change in temperature takes place.) (See fig. 20-6 (D).)

Ceramic capacitors are color-coded as shown in figure 20-7.

The color code is the same as for molded capacitors except for certain values of multipliers and temperature coefficients. Table 20-4 shows the color code for ceramic capacitors. In the temperature coefficient column, the heading ''parts per million per degree centigrade'' means the amount the capacitance may change in micromicrofarads for each million micromicrofarads of rated value when the temperature changes by 1 degree centigrade. For example, the figure ''-30'' in this column would mean that the capacitance of a 1,000,000-micromicrofarad capacitor would decrease to 999,970 micromicrofarads if the temperature increased 1 degree centigrade.

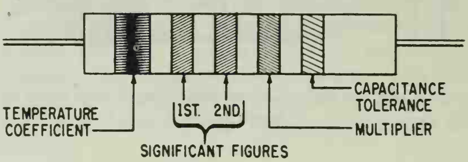


Figure 20-7.—Color code for ceramic capacitors.

Color	Significant figure	Multiplier	Tolerance of capacitance		
			Capacitors of value greater than 10 mmfd. in percent	Capacitors of 10 mmfd. or less in mmfd.	Temperature coefficient parts per million per degree, centigrade
BLACK	0	1	20(M)	2.0(G)	0
BROWN	1	10	1(F)	- - -	-30
RED	2	100	2(G)	- - -	-80
ORANGE	3	1,000	- - -	- - -	-150
YELLOW	4	10,000	- - -	- - -	-220
GREEN	5	100,000	5(J)	0.5(D)	-330
BLUE	6	1,000,000	- - -	- - -	-470
VIOLET	7	10,000,000	- - -	- - -	-750
GRAY	8	0.01	- - -	0.25(C)	+ 30
WHITE	9	0.1	10(K)	1.0(F)	+550

Table 20-4. – Color code for ceramic capacitors.

Transformers

Chapter 13 of this training course describes several different types of transformers. Since it is essential that all windings be correctly connected, the technician should understand the coding used in marking transformer leads.

Small power transformers, of the size used in electronic equipment, are generally color coded as shown in figure 20-8. In an untapped primary, both leads are black. If the primary is tapped, one lead is common and is colored black, the tap lead is black and yellow, and the other lead is black and red.

On the transformer secondary, the high-voltage winding has two red leads if untapped, or two red leads and a yellow tap lead if tapped. On the rectifier filament windings, yellow leads are used across the whole winding, and the tap lead is yellow and blue. If there are other filament windings, they will be either green, brown, or slate. The tapped wire will be yellow in combination with one of the colors just named, that is green and yellow, brown and yellow, or slate and yellow.

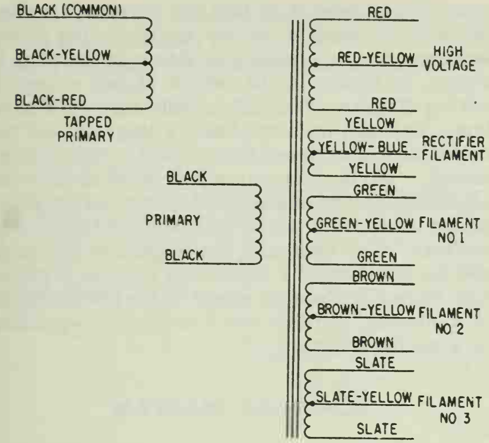

BLACK (COMMON)
BLACK-YELLOW
BLACK-RED
TAPPED PRIMARY
BLACK
PRIMARY
BLACK
RED
RED-YELLOW
HIGH VOLTAGE
RED
YELLOW
YELLOW-BLUE
RECTIFIER FILAMENT
YELLOW
GREEN
GREEN-YELLOW
FILAMENT NO 1
GREEN
BROWN
BROWN-YELLOW
FILAMENT NO 2
BROWN
SLATE
SLATE-YELLOW
FILAMENT NO 3
SLATE

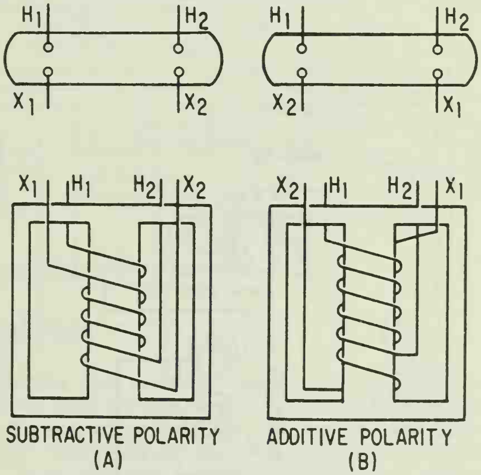
Figure 20-8.—Color coding of small power transformer leads.

The leads of large power transformers, such as those used for shipboard lighting and public utilities, are marked with numbers, letters, or a combination of both. This type of marking is shown in figure 20-9. Terminals for the high-voltage windings are marked $H1$, $H2$, $H3$, and so forth. The increasing numerical subscript designates an increasing voltage. Thus, the voltage between $H1$ and $H3$ is higher than the voltage between $H1$ and $H2$.

The secondary terminals are marked $X1$, $X2$, $X3$, and so forth. There are two types of markings that may be employed on the secondaries. These are shown in figure 20-9. When the $H1$ and $X1$ leads are brought out on the same side of the transformer (fig. 20-9 (A)), the polarity is called SUBTRACTIVE. The reason this arrangement is called subtractive is as follows: If the $H1$ and $X1$ leads are connected and a reduced voltage is applied across the $H1$ and $H2$ leads, the resultant voltage which appears across the $H2$ and $X2$ leads in the series circuit formed by this connection will equal the difference in the voltages of the two windings. The voltage of the low-voltage winding opposes that of the high-voltage winding and subtracts from it, hence the term "subtractive polarity."

When the $H1$ and $X1$ leads are brought out on opposite corners of the transformer (fig. 20-9 (B)), the polarity is ADDITIVE. Navy shipboard transformers have additive polarity. If the $H1$ and $X2$ leads are connected and a reduced voltage is applied across the $H1$ and $H2$ leads, the resultant voltage across the $H2$ and $X1$ leads in the series circuit formed by this connection will equal the sum of the voltages of the two windings. The voltage of the low-voltage winding aids the voltage of the high-voltage winding and adds to it, hence the term "additive polarity."

Polarity markings do not indicate the internal voltage stress in the windings but are useful only in making external connections between transformers, as previously mentioned.


H1
H2
X1
X2
H1
H2
X2
X1
X1
H1
H2
X2
X2
H1
H2
X1

SUBTRACTIVE POLARITY (A)

ADDITIVE POLARITY (B)

Figure 20-9.—Polarity markings for large transformers.

Drawings

There are many different types of drawings, but it would be impractical to attempt to discuss all of them. Therefore, only those drawings that you, the technician, are apt to use frequently will be explained.

For each ship or aircraft there is a master electrical drawing. This drawing shows the entire electrical system and includes such information as power generation, distribution, and utilization. You can easily realize that because of size it would be impractical for the entire electrical drawing to be made available each time information concerning a particular circuit was needed. Therefore, needed sections of this drawing are made available to the technician who maintains that particular part of the system. These sections are usually placed in maintenance manuals.

Many different names are used to describe the various drawings that are constructed to aid in the understanding of electrical systems and equipments. Most all of these drawings are adaptations of some section of the master drawing. Some of the names used to identify particular types of drawings are isometric, expanded, master, wiring, schematic, pictorial, orthographic, and elementary.

The drawings that will be used most often in connection with maintenance work are the wiring diagram and the schematic diagram.

WIRING DIAGRAM

In a wiring diagram the structural parts of a circuit are shown in a simplified form and are generally arranged so that the physical location of parts is similar to the layout in the actual equipment. An example of this type drawing is shown in figure 20-10, which shows a typical wiring diagram of an automobile electrical system. Through the use of such a diagram, the location and interconnection of parts can be determined. Wiring diagrams are often used in the assembly and maintenance of electrical and electronic circuits in which the placement of parts is critical. For example, the lengths of the leads and the position of a capacitor, coil, or resistor may have a noticeable effect on the performance of a circuit, and this could be clearly specified on a wiring diagram.

SCHEMATIC DIAGRAM

In a schematic diagram (generally called simply a "schematic"), parts are represented by symbols, and may be arranged quite differently from their actual physical arrangement.

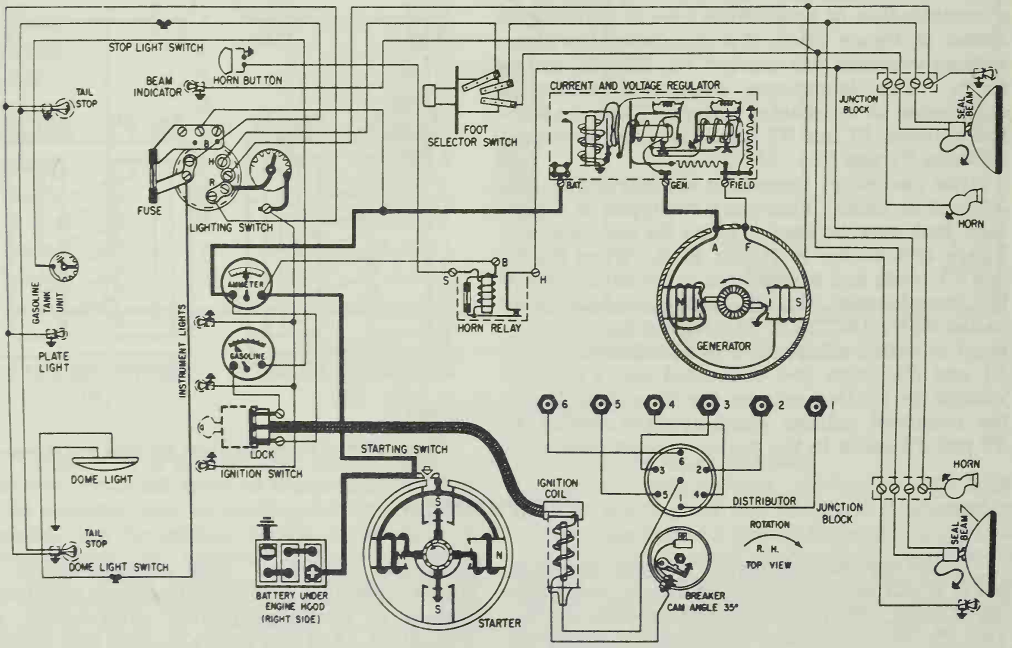

STOP LIGHT SWITCH
BEAM INDICATOR
HORN BUTTON
TAIL STOP
FUSE
B
H
R
LIGHTING SWITCH
FOOT SELECTOR SWITCH
CURRENT AND VOLTAGE REGULATOR
BAT.
GEN.
FIELD
JUNCTION BLOCK
SEAL BEAM
HORN
A
F
S
GENERATOR
B
S
H
HORN RELAY
GASOLINE TANK UNIT
PLATE LIGHT
INSTRUMENT LIGHTS
AMMETER
GASOLINE
LOCK
IGNITION SWITCH
STARTING SWITCH
DOME LIGHT
TAIL STOP
DOME LIGHT SWITCH
BATTERY UNDER ENGINE HOOD (RIGHT SIDE)
S
N
S
STARTER
IGNITION COIL
6
5
4
3
2
1
DISTRIBUTOR
ROTATION
R. H.
TOP VIEW
BREAKER CAM ANGLE 35°
JUNCTION BLOCK
HORN
SEAL BEAM

Figure 20-10.—Wiring diagram of automobile electrical system.

Figure 20-11 is a schematic of the same electrical system shown in figure 20-10. Since this type of diagram is much easier to draw and more compact than a wiring diagram, it is frequently used in connection with troubleshooting and maintenance, particularly in complicated electrical and electronic equipment.

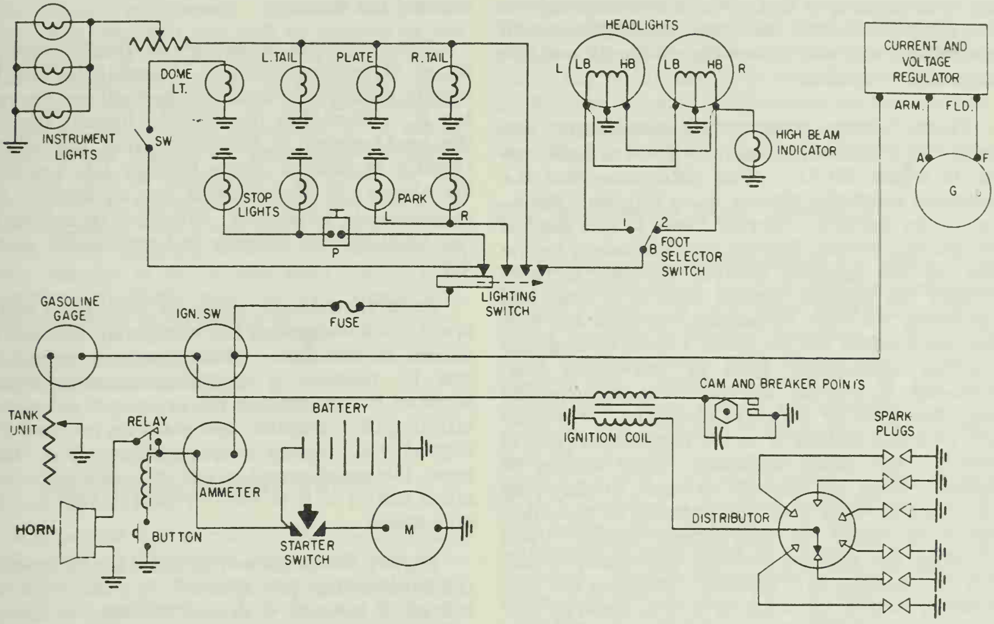

INSTRUMENT LIGHTS
DOME LT.
SW
L.TAIL
PLATE
R.TAIL
STOP LIGHTS
P
PARK
L
R
LIGHTING SWITCH
HEADLIGHTS
L
LB
HB
LB
HB
R
HIGH BEAM INDICATOR
1
2
B
FOOT SELECTOR SWITCH
CURRENT AND VOLTAGE REGULATOR
ARM.
FLD.
A
F
G
GASOLINE GAGE
IGN. SW
FUSE
TANK UNIT
RELAY
BATTERY
AMMETER
HORN
BUTTON
STARTER SWITCH
M
CAM AND BREAKER POINTS
IGNITION COIL
SPARK PLUGS
DISTRIBUTOR

Figure 20-11.—Schematic diagram of automobile electrical system.

Circuit Analysis

You cannot hope to work effectively on a circuit or system you do not understand. Before attempting to make adjustments or correct faults in a circuit, you must first know at least the following:

1. What the circuit is supposed to do in normal operation, and how to operate it.
2. What each part or piece of equipment in the circuit contributes, and how each functions.
3. The location of every part, and routing of conductors.
4. The most likely cause of any given malfunction.
5. The best places to "get into" the circuit for making tests.

If you need any or all of this information, refer to the maintenance manual or master diagram for a particular circuit or system. These publications are prepared by the builder of the ship or aircraft, and contain the most complete descriptions and explanations available.

Also included in these manuals are wiring and schematic diagrams. After the purpose and operation of a circuit is understood, these diagrams are extremely useful in analyzing the details of its installation and operation. They show actual electrical connections between various parts and points in the circuit. When using these diagrams, you can start at the source of power for a particular circuit, trace along the conductors through control devices such as resistors, coils, capacitors, switches, connecting plugs, terminal points, the load, and finally back to the source. Thus, you gain a mental picture of the whole circuit before attempting to work on it. (See figs. 20-10 and 20-11.) By thoroughly analyzing the schematic or wiring diagram for a circuit and then operating it to observe the fault, you should have a pretty good idea of WHAT and WHERE a trouble is before you ever pick up a tool. For instance, suppose you have been told that the headlights on an automobile are not operating properly and you must make repairs.

First, before going to the automobile, you study the schematic diagram (for example, the one in figure 20-11). You determine that the complete headlight circuit is as follows: Starting at the battery, current flows to one side of the starter switch, through the ammeter, to one side of the ignition switch, through a fuse, through the lighting switch when it is down and contacting all four terminals, through the foot selector switch, out terminal 1 or 2, through the selected high-beam (HB) or low-beam (LB) filaments, to ground, and thence back to the battery, one side of which is grounded. When the foot selector switch is in the high-beam (No. 2) position, the beam indicator lamp should be lighted. With the circuit in mind, or carrying a schematic with you, you proceed to the automobile to make an operational check. Upon actuating the lighting switch, you observe that both low beams are lighted. Stepping the foot selector switch to position 2, you observe that the beam indicator lamp is operating, but only the left high-beam headlight is operating. With a glance at the schematic, this indicates that the wiring is sound between terminal 2 and the beam indicator lamp, and between terminal 2 and the left high-beam filament. It also shows that power is being delivered to the right high-beam filament, even though it is not lighting. This indicates that the trouble is in the right headlight. You now know WHERE the trouble is, simply by studying the schematic and operating the circuit. You should also have an idea of WHAT the trouble is (burned-out high-beam filament). It is now time to TURN OFF THE POWER, take up your tools, and go to work on the inoperative headlight.

After exposing the rear terminals of the headlight, you disconnect the wiring and make a continuity check through the high-beam filament with an ohmmeter. To your surprise, the filament checks good. You know that power has been reaching the right high-beam terminal, because it also supplies power to the left high-beam which works properly. Since power is reaching the filament terminal, and the filament is good, this can only mean that the connection is poor. Cleaning and tightening the connection should correct the fault.

The foregoing procedure is usually referred to as "troubleshooting". Troubleshooting and repair consists in locating the fault and correcting it. Repairing the trouble usually involves the replacement of defective parts, but locating trouble is often a more tedious job, requiring knowledge of the system or equipment plus mechanical know-how. Efficient troubleshooting requires an orderly and systematic procedure.

As a technician, much of your time will be spent troubleshooting the equipment you are required to maintain. This is reason enough for you to become a proficient troubleshooter. Much of the equipment you are required to maintain is quite complex, and you may feel that it is beyond your ability to keep it operative. However, the most complex job will usually become much easier if it is first broken up into successive steps.

Figure 20-12 shows, in chart form, a general troubleshooting procedure. The steps given in blocks 1 through 5 are to be used in locating trouble, and the steps given in blocks 6 and 7 are used in making repairs. Steps 2, 3, 4, and 5 may sometimes be eliminated, but never steps 6 and 7.

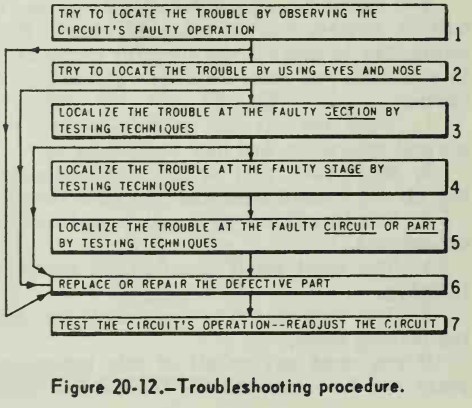

TRY TO LOCATE THE TROUBLE BY OBSERVING THE CIRCUIT'S FAULTY OPERATION
1
TRY TO LOCATE THE TROUBLE BY USING EYES AND NOSE
2
LOCALIZE THE TROUBLE AT THE FAULTY SECTION BY TESTING TECHNIQUES
3
LOCALIZE THE TROUBLE AT THE FAULTY STAGE BY TESTING TECHNIQUES
4
LOCALIZE THE TROUBLE AT THE FAULTY CIRCUIT OR PART BY TESTING TECHNIQUES
5
REPLACE OR REPAIR THE DEFECTIVE PART
6
TEST THE CIRCUIT'S OPERATION--READJUST THE CIRCUIT
7

Figure 20-12.—Troubleshooting procedure.

Maintenance Publications

Many different maintenance publications are written to aid naval technicians in installing, adjusting, maintaining, and testing electrical and electronic equipment. Most of the publications that you will use will be written by the manufacturer of the equipment or by the Navy. These publications usually follow a prescribed pattern and are written so that they present the information in such style that it is easily understood and covers the operation and maintenance procedures thoroughly. In order for you to perform the duties of your job efficiently, it will be necessary for you to refer to these publications. The primary objective of this section of this chapter is to let you know that written material is available and that you should formulate the habit of referring to it.

A brief description of some of the more common publications will be given.

BUREAU OF SHIPS MAINTENANCE PUBLICATIONS

Publications that pertain to the operation and maintenance of electrical equipment and systems are kept in the log room, which is an office of the engineering department. It is important to refer to the applicable publications before working on any equipment or circuits with which you are not thoroughly familiar.

Publications of primary interest to the technician are (1) manufacturers' instruction books, (2) *Bureau of Ships Technical Manual*, (3) *Ship Information Book*, Volume 3, and (4) ship's plans.

Manufacturers Instruction Books

Manufacturers' instruction books contain technical information and instructions for the operation and maintenance of specific apparatus. This information usually includes a general description of the equipment, principles of operation, installation instructions, operating data, maintenance procedures, and safety precautions.

On most ships, instruction books are issued to responsible personnel who must sign custody receipts.

Bureau Of Ships Technical Manual

The Bureau of Ships Technical Manual is the most important Bureau of Ships publication. This manual contains the administrative and engineering instructions for the use of the engineering department. It describes methods of conducting tests, procedures for making repairs, and many helpful maintenance suggestions. It is the official authority on operating procedures.

Ship Information Book, Volume 3

The General Specifications for Ships of the United States Navy require that the contractor furnish copies of the *Ship Information Book*, which consists of several volumes, to each ship built in accordance with these specifications. Power and Lighting, Volume 3 of the *Ship Information Book* serves a particular ship, and replaces the *Record of Electrical Installations and Electrically Operated Auxiliaries*, previously required. Volume 3 consists of two parts. Part 1 contains a general description, and design information of each electrical auxiliary and equipment including the interior communications systems. Part 2 contains the manufacturers' and shipbuilders' test data. This part is particularly valuable as a basis for comparison of test results obtained after the equipment has operated over a period of time.

Ship's Plans

A complete file of standard plans and blueprints is available in the log room for reference and study. At the time a vessel is delivered, the shipbuilder furnishes a set of blueprints to the commanding officer via the supervisor of shipbuilding. These blueprints are in accordance with a list of working plans corrected to show the equipment as installed. Two copies of the *Ship's Plan Index* are also furnished to the ship. This index lists all plans under the cognizance of the Bureau of Ships which apply to the vessel concerned.

The plans furnished to the ship include wiring diagrams of all circuits, lists of telephones, loudspeakers, microphone control stations, voice tubes, calls, message-passing facilities, assembly plans, and wiring diagrams of interior communication and action cutout switchboards and panels; arrangement of electrical equipment in the ship control, command, and plotting stations; and a summary of interior communication and fire control equipment.

BUREAU OF NAVAL WEAPONS MAINTENANCE PUBLICATIONS

(NOTE: A relatively recent Department of the Navy change affects the designation of many aeronautical publications. As of 1 December, 1959 all responsibilities of the Bureau of Aeronautics were transferred to the Bureau of Naval Weapons. Publications that were already printed carry a BUAER designation. As new publications are printed they carry a BUWEP designation.)

The *Naval Aeronautic Publications Index*, NavWeps 00-500, contains a listing of all available naval aeronautic publications. These publications relate to the various naval aircraft and the equipment that is installed in them, as well as associated test equipment. The index is kept current through semiannual revisions. By referring to this index, the technician should be able to determine the identifying number and title of any publication that relates to the equipment he must maintain.

Handbooks

For each model of airborne electronic equipment, four handbooks are prepared. These are (1) the *Handbook of Operating Instructions* (HOI), (2) the *Handbook of Service Instructions* (HSI), (3) the *Handbook of Overhaul Instructions*(O/H), and (4) the *Illustrated Parts Breakdown* (IPB). These handbooks, which are authorized for publication by the Chief of the Bureau of Naval Weapons, contain information based on the results of countless tests and checks. This information will assist the technician and operator in obtaining the best possible performance from the equipment.

The *Handbook of Operating Instructions* contains information pertaining to the operation of the specific equipment and the necessary checks and adjustments required for obtaining optimum operation. This handbook is divided into the following sections—(1) a general description of the equipment, (2) the operating procedures, (3) the operating checks and adjustments, and (4) provisions for emergency operation of the system.

The *Handbook of Service Instructions* presents information on preparing the specific equipment for use. It also tells how to maintain this equipment in an operational squadron, or supporting activity. The handbook is divided into sections which include such information as general principles of operation, special test equipment and tools needed for testing and adjusting the equipment, preparation for use and reshipment, theory of operation, maintenance instructions, and complete schematic, wiring, voltage, and resistance diagrams along with cabling charts for connection of the equipment units.

The *Handbook of Operating Instructions*, the *Handbook of Service Instructions*, and the *Illustrated Parts Breakdown* can be of most help to the technician at the operating level. The *Handbook of Overhaul Instructions* finds greater use at higher levels of maintenance.

THE TECHNICAL LIBRARY

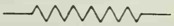
In order that all necessary maintenance publications may be procured, properly filed, kept current, and made available to persons who need them, technical libraries are established.

The technical library contains all letter publications and technical manuals that pertain to the equipment to be maintained. In addition, material of a generally informative nature and also publications useful for training purposes may be available. The technical library should be kept in an orderly manner and its facilities made available to all personnel needing them. When many people use the library, it is essential that a checkout system be set up so that publications may be easily located when needed, and will not be misplaced.

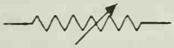
If the technical library contains classified publications, a system is set up that will insure adequate security for its stowage and issuance. Proper procedures for the stowage and handling of classified matter are given in the *Security Manual for Classified Information*, OpNav Instruction 5510.1 series.

QUIZ

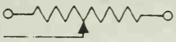
1. A molded capacitor on which the top row of dots (left to right) is silver, brown, and gray and the bottom row (left to right) is yellow, gold, and orange will have a value of
   a. 0.018 mfd.
   b. 18 mfd.
   c. 0.183 mfd.
   d. 183 mfd.
2. The publication that is the official authority on operating procedures is the
   a. Bureau of Ships Technical Manual
   b. Handbook of Operating Instructions
   c. Handbook of Service Instructions
   d. Ship Information Book, Vol. III
3. The electrical symbol used to indicate a potentiometer is
   a.



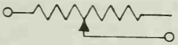
   b.



   c.



   d.



4. The lower left dot in a five-dot capacitor indicates the
   a. multiplier
   b. tolerance
   c. working voltage
   d. characteristic
5. Small power transformer primary leads are color coded
   a. red
   b. black
   c. green
   d. yellow
6. The temperature coefficient of a ceramic capacitor is indicated by the
   a. first dot
   b. last dot
   c. first band
   d. last band
7. A carbon resistor color coded red, blue, green, and gold would indicate a tolerance of
   a. 2%
   b. 5%
   c. 10%
   d. 20%
8. A carbon resistor color coded brown, black, and silver has a resistance value of
   a. 0.01Ω
   b. 0.1Ω
   c. 1Ω
   d. 10Ω
9. The secondary high voltage windings of a small power transformer are color coded
   a. black
   b. green
   c. white
   d. red
10. Before making any adjustments on a faulty circuit, the maintenance man should
   a. check all resistors and capacitors in the circuit
   b. make sure he understands what the circuit is supposed to do in normal operation
   c. check the circuit power supply
   d. observe the circuit's faulty operation
11. The value of a radial carbon resistor with a red end, blue body, and an orange dot would be
   a. 26,000 Ω ± 20%
   b. 6,300 Ω ± 20%
   c. 3,600 Ω ± 20%
   d. 62,000 Ω ± 20%
12. The drawings most often used in maintenance work are
   a. master electrical drawings and schematics
   b. schematics and wiring diagrams
   c. wiring diagrams and isometric drawings
   d. isometric drawings and schematics
13. In a standard Navy circuit drawing 1 milliampere, the power rating of a 4-megohm resistor should be
   a. 3 watts
   b. 4 watts
   c. 5 watts
   d. 6 watts
14. A molded capacitor on which the top row of dots (left to right) is red, violet, and yellow and the bottom row of dots (left to right) is green, silver, and orange will have a voltage rating of
   a. 200 volts
   b. 300 volts
   c. 400 volts
   d. 500 volts
15. The type of diagram that is consulted to find location and interconnection of parts is called a
   a. schematic diagram
   b. master diagram
   c. wiring diagram
   d. pictorial diagram
16. The Naval Aeronautics Publications Index, NavWeps 00-500,
   a. contains a list of parts available for issue in supply
   b. contains a list of equipment and material necessary to place an activity in readiness condition
   c. lists publications currently in effect
   d. is revised annually

CHAPTER 21

SAFETY

In the performance of your duties as a technician you will install, maintain, and repair electrical and electronic equipment in which dangerously high voltages are frequently present. This work is often done in very limited spaces. Among the hazards of this work are electric shock, electrical fires, harmful gases which are sometimes generated by faulty electrical and electronic devices, and injuries which may be caused by the improper use of tools.

Because of these dangers, you should be aware that the formation of safe and intelligent work habits is fully as important as your knowledge of electrical equipment. One of your primary objectives should be to train yourself to recognize and correct dangerous conditions and to avoid unsafe acts. You must also know the authorized methods for dealing with fires of electric origin, for treating burns, and for giving artificial respiration to persons suffering from electric shock.

Under the heading "Basic Precepts," the *United States Navy Safety Precautions* (OpNav 34P1) makes the following statement:

"Most accidents which occur in noncombat operations can be prevented if the full cooperation of personnel is gained and vigilance is exercised to eliminate unsafe acts."

This publication then gives the following general safety rules which apply to personnel in all types of activities:

"Each individual concerned shall strictly observe all safety precautions applicable to his work or duty."

"a. REPORTING UNSAFE CONDITIONS. Each individual concerned shall report any unsafe condition, or any equipment or material which he considers to be unsafe.

"b. WARNING OTHERS. Each individual concerned shall warn others whom he believes to be endangered by known hazards or by failure to observe safety precautions.

"c. PERSONAL PROTECTIVE EQUIPMENT. Each individual concerned shall wear or use protective clothing or equipment of the type approved for the safe performance of his work or duty.

"d. REPORT OF INJURY OR ILL HEALTH. All personnel shall report to their supervisors any injury or evidence of impaired health occurring in the course of work or duty.

"e. EMERGENCY CONDITIONS. In the event of an unforeseen hazardous occurrence, each individual concerned is expected to exercise such reasonable caution as is appropriate to the situation."

Electrical Safety Precautions

EFFECTS OF ELECTRIC SHOCK

Electric shock may cause instant death or may cause unconsciousness, cessation of breathing, and burns of all degrees. If a 60-cycle alternating current is passed through a person from hand to hand or from hand to foot, the effects when current is gradually increased from zero are as follows:

1. At about 1 milliampere (0.001 ampere) the shock can be felt.

2. At about 10 milliamperes (0.010 ampere) the shock is severe enough to paralyze muscles so that a person is unable to release the conductor.

3. At about 100 milliamperes (0.100 ampere) the shock is fatal if it lasts for one second or more.

IT IS IMPORTANT TO REMEMBER THAT CURRENT IS THE SHOCK FACTOR RATHER THAN THE AMOUNT OF VOLTAGE.

You should clearly understand that the resistance of the human body is not great enough to prevent fatal shock from a voltage of as low as 115 volts. In many cases, voltages less than 115 volts are fatal. When the skin is dry, it has a high resistance. The resistance may be high enough to protect a person from a fatal shock even if one hand touches a high voltage while another part of the body touches the chassis or another ground.

Contact resistance decreases when the skin is moist and body resistance may drop to as low as 300 ohms. With this low body resistance, it can be seen that a very low voltage could supply enough current to cause death.

GENERAL SAFETY PRECAUTIONS IN ELECTRICAL MAINTENANCE

Because of the possibility of injury to personnel, the danger of fire, and possible damage to material, all repair and maintenance work on electrical equipment should be performed only by duly authorized and assigned persons.

When any electrical equipment is to be overhauled or repaired, the main supply switches or cutout switches in each circuit from which power could possibly be fed should be secured in the open position and tagged. The tag should read, "This circuit was ordered open for repairs and shall not be closed except by direct order of...." (usually the person directly in charge of the repairs). After the work has been completed, the tag (or tags) should be removed by the same person.

The covers of fuse boxes and junction boxes should be kept securely closed except when work is being done. Safety devices such as interlocks, overload relays, and fuses should never be altered or disconnected except for replacements. Safety or protective devices should never be changed or modified in any way without specific authorization.

The interlock switch is ordinarily wired in series with the power-line leads to the electronic power supply unit, and is installed on the lid or door of the enclosure so as to break the circuit when the lid or door is opened. A true interlock switch is entirely automatic in action; it does not have to be manipulated by the operator. Multiple interlock switches, connected in series, may be used for increased safety. One switch may be installed on the access door of a device, and another on the cover or the power-supply section. Complex interlock systems are provided when several separate circuits must be opened for safety.

Because electrical and electronic equipment may have to be serviced without deenergizing the circuits, interlock switches are constructed so that they can be disabled by the technician. However, to minimize the danger of disabling them accidentally, they are generally located in such a manner that a certain amount of manipulation is necessary in order to operate them.

Fuses should be removed and replaced only after the circuit has been deenergized. When a fuse blows, it should be replaced only with a fuse of the same current and voltage ratings. When possible, the circuit should be carefully checked before making the replacement, since the burned-out fuse is often the result of circuit fault.

HIGH-VOLTAGE PRECAUTIONS

Personnel should never work alone near high-voltage equipment. Tools and equipment containing metal parts, such as brushes and brooms, should not be used in any area within four feet of high-voltage circuits or any electric wiring having exposed surfaces. The handles of all metal tools, such as pliers and cutters, should be covered with rubber insulating tape. (The use of plastic or cambric sleeving or of friction tape alone for this purpose is prohibited.) It is also necessary to insulate the shanks of certain screwdrivers (particularly those used inside electronic equipment) with insulating sheaths. Only 3/16 of an inch of the blade need be exposed. Where it is not practicable to tape or otherwise insulate a surface, electricians' insulating varnish may be used.

Before a worker touches a capacitor which is connected to a deenergized circuit, or which is disconnected entirely, he should short-circuit the terminals to make sure that the capacitor is completely discharged. Grounded shorting prods should be permanently attached to workbenches where electronic devices are regularly serviced.

Do not work on any type of electrical apparatus with wet hands or while wearing wet clothing, and do not wear loose or flapping clothing. The use of thin-soled shoes with metal plates or hobnails is prohibited. Safety shoes with nonconducting soles should be worn if available. Flammable articles, such as celluloid cap visors, should not be worn.

Before working on electronic or electrical apparatus, all rings, wristwatches, bracelets, and similar metal items should be removed. Care should be taken that the clothing does not contain exposed zippers, metal buttons, or any type of metal fasteners.

Warning signs and suitable guards should be provided to prevent personnel from coming into accidental contact with high voltages.

WORK ON ENERGIZED CIRCUITS

Insofar as is practicable, repair work on energized circuits should NOT be undertaken. When repairs on operating equipment must be made in order to make proper adjustments, every known safety precaution should be carefully observed. Ample light for good illumination should be provided; and the worker should be insulated from ground with some suitable nonconducting material such as several layers of dry canvas, dry wood, or a rubber mat of approved construction. The worker should, if possible, use only one hand in accomplishing the necessary repairs, keeping the other hand well away from the energized circuit. Helpers should be stationed near the main switch or the circuit breaker so that the equipment can be deenergized immediately in case of emergency. A man qualified in first aid for electric shock should stand by during the entire period of the repair.

GROUNDING OF PORTABLE ELECTRICAL EQUIPMENT

Navy specifications for portable tools require that the electric cord for such tools be provided with a distinctively marked ground wire in addition to the conductors for supplying power to the tool. The end of the ground wire within the tool must be connected to the tool's metal housing. The other end must be connected to ground. For this ground connection, specially designed grounded-type plugs and receptacles, which automatically make this connection when the plug is inserted in the receptacle, must be used.

Portable tools not provided with the grounded-type plug, and miscellaneous portable electric equipment, which do not have a cord with a grounded conductor and grounded plug, must be provided with a 3-conductor cord and with a standard Navy grounded-type plug. The ground wire must be connected to a positive ground, and the total resistance from the tool enclosure to the ground to which it is connected must not exceed a small fraction of an ohm. Extreme care must be exercised to see that the ground connection is made correctly. If the grounding conductor, which is connected to the metallic equipment casing, is connected by mistake to a line contact of the plug, a dangerous potential will be placed on the equipment casing. This might easily result in a fatal shock to the operator.

BATTERY SAFETY PRECAUTIONS

The principal hazard in connection with batteries is the danger of acid burns when refilling or handling batteries. These burns can be prevented by the proper use of eyeshields, rubber gloves, rubber aprons, and rubber boots with nonslip soles. The rubber boots and apron need be worn only when batteries are being refilled. It is a good practice, however, to wear the eyeshields whenever working around batteries to prevent the possibility of acid burns of the eyes. Wood slat floorboards, if kept in good condition, are helpful in preventing slips and falls as well as electric shock from the high-voltage side of charging equipment.

Another hazard is the danger of explosion due to the ignition of hydrogen gas given off during the battery charging operation. This is especially true where the accelerated charging method is used. Open flames or smoking should not be permitted in the battery charging room, and the charging rate should be held at a point that will prevent the rapid liberation of hydrogen gas. Manufacturers' recommendations as to the charging rates for various size batteries should be closely followed, and a shop exhaust system should be used.

Particular care should be taken by battery men to prevent short circuits while batteries are being charged, tested, or handled, because of the danger of serious burns and explosion of any accumulated hydrogen gas as a result of the spark generated.

PRECAUTIONS WITH CHEMICALS

Volatile liquids such as insulating varnish, lacquer, turpentine, and kerosene are dangerous when used near energized electronic or electrical equipment because of the danger of igniting the fumes by sparks. When these liquids are used in spaces containing nonoperating equipment, be sure that there is sufficient ventilation to avoid an accumulation of fumes and that all fumes are cleared before the equipment is energized.

Alcohol should never be used for cleaning electrical equipment since it not only constitutes a fire hazard but it also results in damage to many kinds of insulation. Neither should carbon tetrachloride be employed as a cleaning agent. Unlike alcohol, the use of carbon tetrachloride does not create a fire hazard; but it is dangerous because of the injurious effects of breathing its vapor. Also, it forms an insulating film on the material to which it is applied. The careless use of carbon tetrachloride may result in headache, dizziness, and nausea. If the fumes are breathed in poorly ventilated spaces, the effect may be loss of consciousness or even death. For these reasons, the use of carbon tetrachloride as a solvent or cleaner has been specifically prohibited in Navy maintenance operations. When cleaning electrical or electronic equipments or parts, always use an approved cleaning agent such as Dry Cleaning Solvent, Federal Specification P-S-661.

Safety From Fire

PREVENTING FIRES

General cleanliness of the work area and of electronic apparatus is essential for the prevention of electrical fires. Oil, grease, and carbon dust can be ignited by electrical arcing. Therefore, electrical and electronic equipment should be kept absolutely clean and free of all such deposits.

Wiping rags and other flammable waste material must always be placed in tightly closed metal containers, which must be emptied at the end of the day's work.

Containers holding paints, varnishes, cleaners, or any volatile solvents should be kept tightly closed when not in actual use. They must be stored in a separate building or in a fire-resisting room which is well-ventilated and where they will not be exposed to excessive heat or to the direct rays of the sun.

FIREFIGHTING

In case of electrical fires, the following steps should be taken:

1. Deenergize the circuit.
2. Call the Fire Department.
3. Control or extinguish the fire, using the correct type of fire extinguisher.
4. Report the fire to the appropriate authority.

For combating electrical fires, use a CO_2 (carbon dioxide) fire extinguisher and direct it toward the base of the flame. Carbon tetrachloride should never be used for firefighting since it changes to phosgene (a poisonous gas) upon contact with hot metal, and even in open air this creates a hazardous condition. The application of water to electrical fires is dangerous; the foam-type fire extinguishers should not be used since the foam is electrically conductive.

In cases of cable fires in which the inner layers of insulation or insulation covered by armor are burning, the only positive method of preventing the fire from running the length of the cable is to cut the cable and separate the two ends.

When selenium rectifiers burn out, fumes of selenium dioxide are liberated which cause an overpowering stench. The fumes are poisonous and should not be breathed. If a rectifier burns out, deenergize the equipment immediately and ventilate the room. Allow the damaged rectifier to cool before attempting any repairs. If possible, move the equipment containing it out of doors. Do not touch or handle the defective rectifier while it is hot since a skin burn might result, through which some of the selenium compound could be absorbed.

Fires involving wood, paper, cloth, or explosives should be fought with water. Water works well on them. Therefore, advantage is taken of its inexpensiveness, availability, and safety in handling.

A steady stream of water does not work in extinguishing fires involving substances like oil, gasoline, kerosene, or paint, because these substances will float on top of the water and keep right on burning. Also, a stream of water will scatter the burning liquid and spread the fire. For this reason, foam or fog must be used in fighting such fires.

Safety Precautions When Using Tools

As a general precaution, be sure that all tools used conform to Navy standards as to quality and type. Use each tool only for the purpose for which it is intended. All tools in active use should be maintained in good repair and all damaged or nonworking tools should be returned to the toolkeeper.

HANDTOOLS

Care must be taken when selecting pliers, side cutters, or diagonal cutters. Pliers or cutters should never be used on nuts or pipefittings. Always hold the pliers or cutters so that the fingers are not wrapped around the handle in such a way that they can be pinched or jammed if the tool slips. When cutting short pieces, take care that parts of the work do not fly and cause injury. Never put extensions on tool handles to increase leverage.

When selecting a screwdriver for electrical work, be sure that it has a nonconducting handle. The screwdriver selected should be of the proper size to fit the screw and should never be used as a substitute for a punch or a chisel. The points of screwdrivers can be kept in proper shape with a file or a grinding wheel.

Use wrenches only if they are right for the job and only if they are in good condition. An adjustable wrench should be faced so that the movable jaw is located forward in the direction in which the handle is to be turned.

PORTABLE POWER TOOLS

All portable power tools should be inspected before use to see that they are clean, well oiled, and in the proper state or repair. The switches should operate normally, and the cords should be clean and free of defects. The case of any electrically driven power tool should be well grounded; and sparking electric tools should never be used in places where flammable gases or liquids or exposed explosives are present.

Drills must be straight, undamaged, and properly sharpened. Tighten the drill securely in the chuck using the key provided; never secure it with pliers or with a wrench. It is important that the drill be set straight and true in the chuck. The work should be firmly clamped and, if of metal, a center punch should be used to score the material before drilling is started.

Be sure that power cords do not come in contact with sharp objects. The cords should not be allowed to kink, nor should they be allowed to come in contact with oil, grease, hot surfaces, or chemicals. When cords are damaged, they should be replaced instead of being patched with tape.

SHOP MACHINERY

In your work as a technician, you may be required to use a few pieces of shop machinery such as a power grinder or a drill press. In addition to the general precautions on the use of tools, there are several other precautions which should be observed when you work with machinery. The more important ones are:

1. Never remove a guard or cover from a running machine.
2. Never operate mechanical or powered equipment unless you are thoroughly familiar with its controls. When in doubt, consult the appropriate instruction or ask someone who knows.
3. Always make sure that everyone is clear before starting or operating mechanical equipment.
4. Never try to clear jammed machinery without first cutting off the source of power.
5. When hoisting heavy machinery (or equipment) by a chain fall, always keep everyone clear, and guide the hoist with lines attached to the equipment.
6. Never plug in portable electric machinery without insuring that the source is the kind of electricity (a.c. or d.c.) called for on the nameplate of the machine.

First Aid

TREATMENT FOR ELECTRICAL SHOCK

Electric shock is a jarring, shaking sensation resulting from contact with electric circuits or from the effects of lightning. The victim usually feels that he has received a sudden blow; and if the voltage is sufficiently high, he may become unconscious. Severe burns may appear on the skin at the place of contact; muscular spasm can occur, causing him to clasp the apparatus or wire which caused the shock and be unable to turn it loose. Electric shock can kill its victim by stopping the heart or by stopping breathing, or both. It may sometimes damage nerve tissue and result in a slow wasting away of muscles that may not become apparent until several weeks or months after the shock was received.

The following procedure is recommended for rescue and care of shock victims:

1. Remove the victim from electrical contact at once, but DO NOT ENDANGER YOURSELF. This can be done by: (1) Throwing the switch if it is nearby; (2) cutting the cable or wires to the apparatus, using an ax with a wooden handle while taking care to protect your eyes from the flash when the wires are severed; (3) use of a dry stick, rope, leather belt, coat, blanket, or any other nonconductor of electricity.
2. Determine whether the victim is breathing. If he is, keep him lying down in a comfortable position. Loosen the clothing about his neck, chest, and abdomen so that he can breathe freely. Protect him from exposure to cold, and watch him carefully.
3. Keep him from moving about. In this condition, the heart is very weak, and any sudden muscular effort or activity on the part of the patient may result in heart failure.
4. Do not give stimulants or opiates. Send for a medical officer at once and do not leave the patient until he has adequate medical care.
5. If the victim is not breathing, it will be necessary to apply artificial respiration without delay, even though he may appear to be lifeless.

RESUSCITATION FROM THE EFFECTS OF ELECTRIC SHOCK

Artificial respiration is the process of promoting breathing by mechanical means. It is used to resuscitate persons whose breathing has stopped, not only as a result of electric shock, but also from causes such as drowning, asphyxiation, strangling, or the presence of a foreign body in the throat.

When a shock victim must be revived, begin artificial respiration as soon as possible. If there is any serious bleeding, stop it first, but do not waste time on anything else. Seconds count; and the longer you wait to begin, the less are the chances of saving the victim. (See fig. 21-1.)

Personnel in all rates and ratings, E-2 and above, are required to be able to administer artificial respiration by the back-pressure arm-lift method and the back-pressure hip-lift method. Detailed coverage on the Navy's standardized procedures on these methods of artificial respiration are given in the *Standard First Aid Training Course,* NavPers 10081. Additional material such as that on pole-top resuscitation, mechanical aids for resuscitation, and treatment during recovery are also contained in this first aid course. Future revisions of NavPers 10081 will contain information on new standardized first aid procedures adopted by the Navy such as the mouth-to-mouth method of resuscitation.

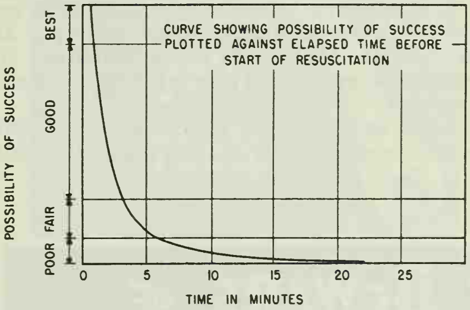


Figure 21-1.—Importance of speed in commencing artificial respiration.

TREATMENT OF BURNS AND WOUNDS

In administering first aid for burns, the objectives are to relieve the pain, to make the patient as comfortable as possible, to prevent infection, and to guard against shock which often accompanies burns of a serious nature. Detailed information on the proper method for treating various types of burns is contained in the *Standard First Aid Training Course,* NavPers 10081.

Any break in the skin is dangerous because it allows germs to enter the wound. Although infection may occur in any wound, it is of particular danger in wounds which do not bleed freely, wounds in which torn tissue or skin falls back into place and so prevents the entrance of air, and wounds which involve crushing of tissues.

Minor wounds should be washed immediately with soap and clean water, dried, and painted with a mild, nonirritating antiseptic. Benzalkonium chloride tincture, which is now found in most Navy first aid kits, is a good antiseptic; it does not irritate the skin but it effectively destroys many of the micro-organisms which cause infection. (Benzalkonium chloride is commonly sold under the name of Zephiran or Zepherin chloride.) Apply a dressing if necessary.

Larger wounds should be treated only by medical personnel. Merely cover the wound with a dry sterile compress and fasten the compress in place with a bandage.

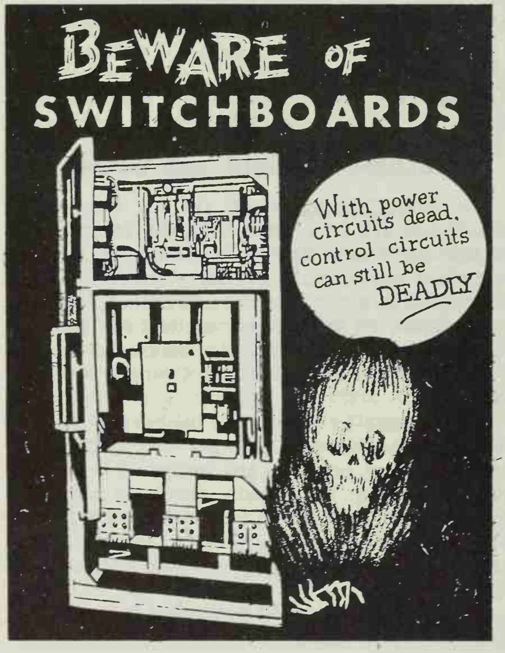
Since the saving of a person's life often depends on prompt and correct first aid treatment, all Navy personnel should become thoroughly familiar with the material in the *Standard First Aid Training Course,* NavPers 10081.

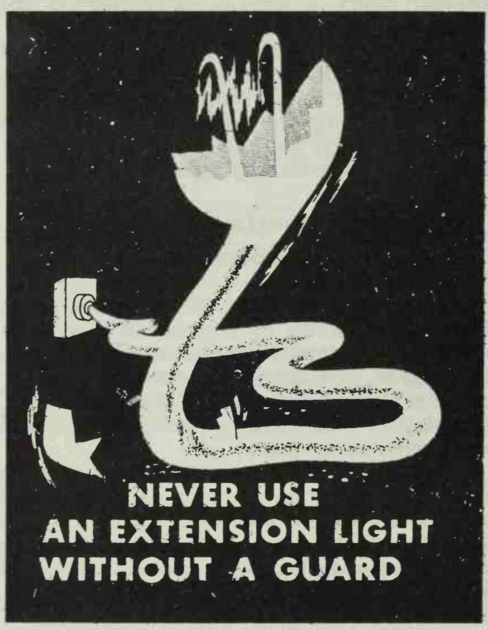
Safety Education

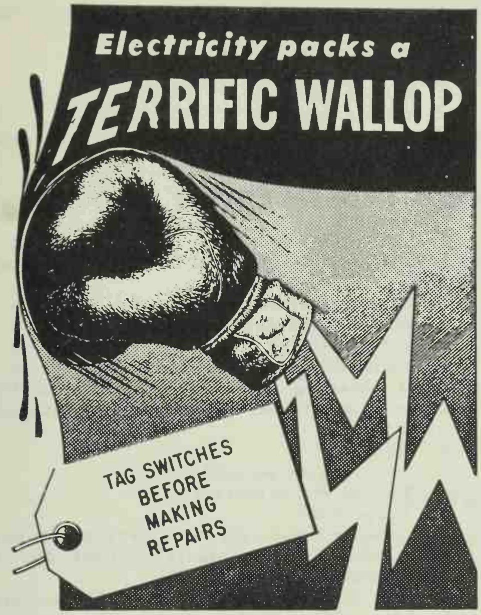
Safety is an all-hand responsibility. It is the job of every person in the Navy to exercise precaution to insure that people will not be injured or killed, or equipment damaged or ruined. Safety information is presented in many different ways — for example: (1) Written material, as given in this chapter; (2) safety bulletins; (3) lectures; (4) movies; (5) courses in first aid; and (6) posters.

Every shop in which you work should emphasize safety. One of the ways in which this can be done is through the use of posters. The Navy makes available numerous safety posters. Some of these are general in nature and some relate to specific types of work. These posters should be placed in a conspicuous area and as new ones are printed they should replace the older ones.

Four of the current posters that relate to shop and electrical safety follow.


BEWARE OF
SWITCHBOARDS
With power circuits dead, control circuits can still be DEADLY





NATIONAL SAFETY COUNCIL

AFTER the job
count your tools

QUIZ

1. It is dangerous to touch a burned-out selenium rectifier when it is hot because
   a. some of the selenium compound could be absorbed through a skin burn
   b. direct current could cause shock
   c. fumes of selenium dioxide could be liberated
   d. all of the above are correct
2. When using an adjustable wrench, it should be so faced that the movable jaw is located
   a. forward in the direction in which the handle is turned
   b. aft of the direction in which the handle is turned
   c. free of all obstructions
   d. between the worker and the work to be performed
3. If electrical or electronic equipment is to be repaired, what must be done before the actual work is begun?
   a. The fuse for the associated circuit must be removed
   b. The main supply switches must be shorted out
   c. A man must be stationed nearby with a fire extinguisher
   d. The main supply switches must be secured open and tagged
4. The handles of all metal tools used for working on electrical circuits should be covered with
   a. friction tape
   b. plastic sleeving
   c. rubber insulating tape
   d. cambric sleeving
5. To check whether a capacitor is completely discharged, a worker should
   a. short-circuit the terminals
   b. take a resistance reading
   c. lightly tap the leads with his finger
   d. none of the above are correct
6. The principal hazard(s) when handling and charging batteries is/are due to the danger of
   a. electrical shock
   b. asphyxiation
   c. acid burns and explosion
   d. acid burns and asphyxiation
7. When fighting an electrical fire, you should use
   a. foam
   b. soda and acid
   c. carbon dioxide
   d. carbon tetrachloride

8. If you desire to drill a hole in metal, always be sure to
   a. apply extra pressure to prevent bucking
   b. use a dull drill and oil
   c. secure the drill in the chuck with a wrench
   d. score the material with a center punch
9. Carbon tetrachloride is specifically prohibited as a cleaning agent because it may
   a. create a fire hazard
   b. cause dizziness and nausea
   c. explode if exposed to an electrical spark
   d. cause blood poisoning
10. Paints and varnishes should be stored in a
    a. tightly closed metal locker
    b. sealed fire-resisting room or separate building
    c. separate building or fire-resisting room which is well-ventilated
    d. warm and sunlit location
11. Damaged cords for power tools should be
    a. coated with flux and covered with rubber tape
    b. repaired with insulating tape
    c. replaced
    d. shortened to remove the damaged section
12. Electrical shock is fatal when ________ of current is passed through a person from hand to hand for one second or more.
    a. 0.10 ampere
    b. 0.01 ampere
    c. 1 milliampere
    d. 10 milliamperes
13. Water is a good firefighting agent on wood, paper,
    a. cloth, or kerosene
    b. cloth, or explosives
    c. oil, or paint
    d. oil, or gasoline
14. The shock factor of electricity is dependent on the amount of
    a. resistance
    b. voltage
    c. current
    d. all of the above
15. In case of an electrical fire, the first step is to
    a. deenergize the circuit
    b. call the fire department
    c. extinguish the fire
    d. notify the proper authority
16. What cleaning agent should be used for cleaning electrical or electronic equipment or parts?
    a. Alcohol
    b. Drycleaning solvent
    c. Carbon tetrachloride
    d. Turpentine
17. The proper treatment for a person who has received a severe electric shock but is still breathing is to
    a. give him an opiate to relieve his anxiety
    b. keep him walking or moving about so that he will not lose consciousness
    c. apply artificial respiration to assist him in breathing
    d. keep him lying down

APPENDIX I

ANSWERS TO QUIZZES

Chapter 1

FUNDAMENTAL CONCEPTS OF ELECTRICITY

1. c.
2. d.
3. d.
4. c.
5. c.
6. b.
7. a.
8. d.
9. c.
10. a.
11. c.
12. b.
13. a.
14. b.
15. d.
16. d.
17. c.
18. a.
19. b.
20. d.
21. d.
22. d.
23. c.
24. d.
25. b.

Chapter 2

BATTERIES

1. c.
2. c.
3. d.
4. c.
5. b.
6. a.
7. d.
8. b.
9. c.
10. c.
11. c.
12. b.
13. b.
14. c.
15. c.
16. c.
17. d.
18. c.
19. a.
20. a.

Chapter 3

THE SIMPLE ELECTRIC CIRCUIT

1. a.
2. b.
3. d.
4. a.
5. b.
6. c.
7. b.
8. c.
9. b.
10. c.
11. b.
12. d.
13. b.
14. b.
15. a.
16. b.
17. a.
18. d.
19. b.
20. b.

Chapter 4

DIRECT-CURRENT SERIES AND PARALLEL CIRCUITS

1. c.
2. a.
3. c.
4. b.
5. c.
6. a.
7. b.
8. b.
9. b.
10. a.
11. a.
12. a.
13. d.
14. b.
15. c.
16. a.
17. a.
18. d.
19. b.
20. d.
21. c.
22. d.
23. a.
24. b.

Chapter 5

DIRECT-CURRENT COMPOUND AND BRIDGE CIRCUITS

1. b.
2. c.
3. d.
4. b.
5. a.
6. c.
7. d.
8. a.
9. d.
10. d.
11. a.
12. c.
13. a.
14. b.
15. d.
16. c.
17. b.
18. a.
19. c.
20. b.

Chapter 6

ELECTRICAL CONDUCTORS AND WIRING TECHNIQUES

1. c.
2. d.
3. d.
4. c.
5. a.
6. b.
7. a.
8. c.
9. a.
10. b.
11. c.
12. c.
13. b.
14. d.
15. c.
16. d.
17. a.
18. b.
19. b.
20. a.

Chapter 7

ELECTROMAGETISM AND MAGNETIC CIRCUITS

1. b.
2. d.
3. b.
4. b.
5. d.
6. c.
7. b.
8. b.
9. a.
10. b.
11. a.
12. c.
13. d.
14. a.
15. a.
16. d.
17. c.
18. c.
19. b.
20. c.
21. c.

Chapter 8

INTRODUCTION TO ALTERNATING-CURRENT ELECTRICITY

1. c.
2. a.
3. d.
4. c.
5. b.
6. d.
7. c.
8. c.
9. b.
10. c.
11. b.
12. b.
13. c.
14. d.
15. b.
16. b.
17. d.
18. a.
19. b.
20. c.
21. c.
22. d.
23. d.
24. a.
25. d.
26. b.
27. c.

Chapter 9

INDUCTANCE AND CAPACITANCE

1. b.
2. c.
3. c.
4. b.
5. a.
6. b.
7. d.
8. d.
9. c.
10. b.
11. c.
12. a.
13. b.
14. a.
15. d.
16. b.
17. a.
18. d.
19. b.
20. d.
21. b.
22. b.
23. a.
24. d.
25. a.

Chapter 10

INDUCTIVE AND CAPACITIVE REACTANCE

1. c.
2. c.
3. c.
4. a.
5. a.
6. b.
7. a.
8. a.
9. d.
10. d.
11. a.
12. d.
13. b.
14. d.
15. a.
16. c.
17. b.
18. b.
19. d.
20. a.
21. a.
22. b.
23. a.

Chapter 11

FUNDAMENTAL ALTERNATING-CURRENT CIRCUIT THEORY

1. b.
2. b.
3. c.
4. a.
5. c.
6. b.
7. d.
8. d.
9. a.
10. c.
11. c.
12. a.
13. a.
14. c.
15. d.
16. d.
17. c.
18. b.
19. c.
20. d.
21. b.
22. a.
23. b.
24. c.

Chapter 12

BASIC ELECTRICAL INDICATING INSTRUMENTS

1. b.
2. c.
3. c.
4. c.
5. b.
6. d.
7. b.
8. c.
9. b.
10. b.
11. a.
12. b.
13. b.
14. c.
15. c.
16. d.
17. a.
18. d.
19. b.
20. d.
21. b.
22. a.
23. c.

Chapter 13

ALTERNATING-CURRENT GENERATORS AND TRANSFORMERS

1. c.
2. c.
3. c.
4. d.
5. d.
6. b.
7. d.
8. a.
9. a.
10. b.
11. d.
12. b.
13. c.
14. c.
15. c.
16. b.
17. a.
18. b.
19. c.
20. a.
21. c.
22. c.

Chapter 14

ALTERNATING-CURRENT MOTORS

1. d.
2. b.
3. d.
4. b.
5. a.
6. a.
7. a.
8. b.
9. d.
10. d.
11. b.
12. b.
13. c.
14. c.
15. d.
16. c.
17. a.
18. d.
19. b.
20. c.
21. d.
22. b.
23. d.
24. b.
25. c.

Chapter 15

DIRECT-CURRENT GENERATORS

1. b.
2. d.
3. b.
4. b.
5. b.
6. d.
7. c.
8. b.
9. b.
10. c.
11. c.
12. b.
13. a.
14. d.
15. a.
16. d.
17. d.
18. c.
19. a.
20. c.
21. c.
22. c.
23. c.
24. a.
25. a.
26. d.
27. a.

Chapter 16

DIRECT-CURRENT MOTORS

1. a.
2. d.
3. c.
4. a.
5. b.
6. b.
7. c.
8. d.
9. d.
10. b.
11. b.
12. c.
13. c.
14. d.
15. b.
16. b.
17. b.
18. c.
19. a.
20. d.
21. a.
22. a.
23. d.
24. c.

Chapter 17

ALTERNATING-CURRENT INSTRUMENTS

1. c.
2. c.
3. c.
4. c.
5. a.
6. a.
7. d.
8. c.
9. d.
10. b.
11. a.
12. d.
13. d.
14. c.
15. c.
16. a.
17. a.
18. a.
19. a.
20. b.
21. b.
22. d.
23. b.
24. d.

Chapter 18

MAGNETIC AMPLIFIERS

1. d.
2. b.
3. c.
4. c.
5. d.
6. d.
7. d.
8. c.
9. b.
10. b.
11. a.
12. c.
13. b.
14. a.
15. c.
16. d.

Chapter 19

SYNCHROS AND SERVOMECHANISMS

1. d.
2. d.
3. c.
4. a.
5. d.
6. b.
7. a.
8. d.
9. a.
10. b.
11. d.
12. c.
13. a.
14. b.
15. a.
16. a.
17. a.
18. c.
19. b.
20. b.
21. a.
22. d.

Chapter 20

ELECTRICAL DRAWINGS AND TECHNICAL MANUALS

1. a.
2. a.
3. c.
4. a.
5. b.
6. c.
7. b.
8. b.
9. d.
10. b.
11. d.
12. b.
13. d.
14. d.
15. c.
16. c.

Chapter 21

SAFETY

1. a.
2. a.
3. d.
4. c.
5. a.
6. c.
7. c.
8. d.
9. b.
10. c.
11. c.
12. a.
13. b.
14. c.
15. a.
16. b.
17. d.

APPENDIX II

NAVY CABLE TYPE AND SIZE DESIGNATIONS

All cables described herein are identified by NAVY CABLE TYPE AND SIZE DESIGNATIONS, which consists of a letter followed by numerals.

I. The TYPE DESIGNATION indicates the type or construction of the cable and and consists of the first letters of the words used in describing the cable:

Example: Type SHFA-Single, Heat and Flame-resistance, Armored.

II. The SIZE DESIGNATION relates to the copper conductors. No set rule has been established for application of SIZE DESIGNATIONS since the numerals used may indicate one or more of the following:

(1) Size of copper conductor.
(2) Stranding of conductors.
(3) Number of copper conductors.
(4) Number of twisted pairs.

Examples of the most common uses of SIZE DESIGNATIONS are given below:

(1) To indicate approximate cross-sectional area of the conductor expressed in thousands of circular mils (abbreviated C.M.).

Example: The conductor area of SHFA-3 is approximately 3000 C.M. (exactly 2828 C.M.)

(2) To indicate approximate cross-sectional area with stranding shown in parentheses.

Example: The conductor area of SRI-2-1/2 (26) is approximately 2500 C.M. (exactly 2613 C.M.), and consists of 26 individual wire strands.

(3) To indicate number of conductors.

Example: MCOP-7 is a cable comprised of seven conductors.

(4) To indicate number of twisted pairs.

Example: TTOP-10 is a 20-conductor cable comprised of 10 twisted pairs.

The following are typical examples of type designations and constructions:

FLA—Four conductor, Lighting, Armored. Varnished cambric or rubber insulation, rubber hose jacket, armored.

MCMB—Multiple Conductor, Marker-Buoy. Rubber insulated identifying colors, steel supporting cable, tape over assembly, tough rubber sheath.

SHFA—Single conductor, Heat and Flame-resistant, Armored. Asbestos-varnished cambric-asbestos insulation, impervious sheath, armored.

THFR—Triple conductor, Heat and Flame-resistant, Radio. Synthetic resin-varnished cambric and felted asbestos insulation, asbestos belt, impervious sheath, armored.

TTHFA—Twisted pairs, Telephone, Heat and Flame-resistant, Armored. Solid conductor, textile wrap or synthetic resin insulation, twisted pair, felted asbestos belt, impervious sheath, armored.

APPENDIX III

GREEK ALPHABET

Name	Capital	Lower Case	Designates
Alpha	Α	α	Angles.
Beta	Β	β	Angles, flux density.
Gamma	Γ	γ	Conductivity.
Delta	Δ	δ	Variation of a quantity, increment.
Epsilon	Ε	ϵ	Base of natural logarithms (2.71828).
Zeta	Ζ	ζ	Impedance, coefficients, coordinates.
Eta	Η	η	Hysteresis coefficient, efficiency, magnetizing force.
Theta	Θ	θ	Phase angle.
Iota	Ι	ι	
Kappa	Κ	κ	Dielectric constant, coupling coefficient, susceptibility.
Lambda	Λ	λ	Wavelength.
Mu	Μ	μ	Permeability, micro, amplification factor.
Nu	Ν	ν	Reluctivity.
Xi	Ξ	ξ	
Omicron	Ο	ο	
Pi	Π	π	3.1416
Rho	Ρ	ρ	Resistivity.
Sigma	Σ	σ	
Tau	Τ	τ	Time constant, time-phase displacement.
Upsilon	Υ	υ	
Phi	Φ	φ	Angles, magnetic flux.
Chi	Χ	χ	
Psi	Ψ	ψ	Dielectric flux, phase difference.
Omega	Ω	ω	Ohms (capital), angular velocity ($2 \pi f$).

APPENDIX IV

COMMON ABBREVIATIONS AND LETTER SYMBOLS

Term	Abbreviation or Symbol
alternating current (noun)	a.c.
alternating-current (adj.)	a-c
ampere	a.
area	A
audiofrequency (noun)	AF
audiofrequency (adj.)	A-F
capacitance	C
capacitive reactance	X_c
centimeter	cm.
conductance	G
coulomb	Q
counterelectromotive force	c.e.m.f.
current (d-c or r.m.s. value)	I
current (instantaneous value)	i
cycles per second	c.p.s.
dielectric constant	K,k
difference in potential (d-c or r.m.s. value)	E
difference in potential (instantaneous value)	e
direct current (noun)	d.c.
direct-current (adj.)	d-c
electromotive force	e.m.f.
frequency	f
henry	h.
horsepower	hp.
impedance	Z
inductance	L
inductive reactance	X_L
kilovolt	kv.
kilovolt-ampere	kv.-a.
kilowatt	kw.
kilowatt-hour	kw.-hr.
magnetic field intensity	H
magnetomotive force	m.m.f.
megohm	M
microampere	μ a.
microfarad	μ f.
microhenry	μ h.
micromicrofarad	μμ f.
microvolt	μ v.
milliampere	ma.
millihenry	mh.
milliwatt	mw.
mutual inductance	M
power	P
resistance	R
revolutions per minute	r.p.m.
root mean square	r.m.s.
time	t
torque	T
volt	v.
watt	w.

APPENDIX V

ELECTRICAL TERMS AND FORMULAS

Terms

AGONIC.—An imaginary line of the earth's surface passing through points where the magnetic declination is 0°; that is, points where the compass points to true north.

AMMETER.—An instrument for measuring the amount of electron flow in amperes.

AMPERE.—The basic unit of electrical current.

AMPERE-TURN.—The magnetizing force produced by a current of one ampere flowing through a coil of one turn.

AMPLIDYNE.—A rotary magnetic or dynamo-electric amplifier used in servomechanism and control applications.

AMPLIFICATION.—The process of increasing the strength (current, power, or voltage) of a signal.

AMPLIFIER.—A device used to increase the signal voltage, current, or power, generally composed of a vacuum tube and associated circuit called a stage. It may contain several stages in order to obtain a desired gain.

AMPLITUDE.—The maximum instantaneous value of an alternating voltage or current, measured in either the positive or negative direction.

ARC.—A flash caused by an electric current ionizing a gas or vapor.

ARMATURE.—The rotating part of an electric motor or generator. The moving part of a relay or vibrator.

ATTENUATOR.—A network of resistors used to reduce voltage, current, or power delivered to a load.

AUTOTRANSFORMER.—A transformer in which the primary and secondary are connected together in one winding.

BATTERY.—Two or more primary or secondary cells connected together electrically. The term does not apply to a single cell.

BREAKER POINTS.—Metal contacts that open and close a circuit at timed intervals.

BRIDGE CIRCUIT.—The electrical bridge circuit is a term referring to any one of a variety of electric circuit networks, one branch of which, the "bridge" proper, connects two points of equal potential and hence carries no current when the circuit is properly adjusted or balanced.

BRUSH.—The conducting material, usually a block of carbon, bearing against the commutator or sliprings through which the current flows in or out.

BUS BAR.—A primary power distribution point connected to the main power source.

CAPACITOR.—Two electrodes or sets of electrodes in the form of plates, separated from each other by an insulating material called the dielectric.

CHOKE COIL.—A coil of low ohmic resistance and high impedance to alternating current.

CIRCUIT.—The complete path of an electric current.

CIRCUIT BREAKER.—An electromagnetic or thermal device that opens a circuit when the current in the circuit exceeds a predetermined amount. Circuit breakers can be reset.

CIRCULAR MIL.—An area equal to that of a circle with a diameter of 0.001 inch. It is used for measuring the cross section of wires.

COAXIAL CABLE.—A transmission line consisting of two conductors concentric with and insulated from each other.

COMMUTATOR.—The copper segments on the armature of a motor or generator. It is cylindrical in shape and is used to pass power into or from the brushes. It is a switching device.

CONDUCTANCE.—The ability of a material to conduct or carry an electric current. It is the reciprocal of the resistance of the material, and is expressed in mhos.

CONDUCTIVITY.—The ease with which a substance transmits electricity.

CONDUCTOR.—Any material suitable for carrying electric current.

CORE.—A magnetic material that affords an easy path for magnetic flux lines in a coil.

COUNTER E.M.F.—Counter electromotive force; an e.m.f. induced in a coil or armature that opposes the applied voltage.

CURRENT LIMITER.—A protective device similar to a fuse, usually used in high amperage circuits.

CYCLE.—One complete positive and one complete negative alternation of a current or voltage.

DIELECTRIC.—An insulator; a term that refers to the insulating material between the plates of a capacitor.

DIODE.—Vacuum tube—a two element tube that contains a cathode and plate; semiconductor—a material of either germanium or silicon that is manufactured to allow current to flow in only one direction. Diodes are used as rectifiers and detectors.

DIRECT CURRENT.—An electric current that flows in one direction only.

EDDY CURRENT.—Induced circulating currents in a conducting material that are caused by a varying magnetic field.

EFFICIENCY.—The ratio of output power to input power, generally expressed as a percentage.

ELECTROLYTE.—A solution of a substance which is capable of conducting electricity. An electrolyte may be in the form of either a liquid or a paste.

ELECTROMAGNET.—A magnet made by passing current through a coil of wire wound on a soft iron core.

ELECTROMOTIVE FORCE (e.m.f.).—The force that produces an electric current in a circuit.

ELECTRON.—A negatively charged particle of matter.

ENERGY.—The ability or capacity to do work.

FARAD.—The unit of capacitance.

FEEDBACK.—A transfer of energy from the output circuit of a device back to its input.

FIELD.—The space containing electric or magnetic lines of force.

FIELD WINDING.—The coil used to provide the magnetizing force in motors and generators.

FLUX FIELD.—All electric or magnetic lines of force in a given region.

FREE ELECTRONS.—Electrons which are loosely held and consequently tend to move at random among the atoms of the material.

FREQUENCY.—The number of complete cycles per second existing in any form of wave motion; such as the number of cycles per second of an alternating current.

FULL-WAVE RECTIFIER CIRCUIT.—A circuit which utilizes both the positive and the negative alternations of an alternating current to produce a direct current.

FUSE.—A protective device inserted in series with a circuit. It contains a metal that will melt or break when current is increased beyond a specific value for a definite period of time.

GAIN.—The ratio of the output power, voltage, or current to the input power, voltage, or current, respectively.

GALVANOMETER.—An instrument used to measure small d-c currents.

GENERATOR.—A machine that converts mechanical energy into electrical energy.

GROUND.—A metallic connection with the earth to establish ground potential. Also, a common return to a point of zero potential. The chassis of a receiver or a transmitter is sometimes the common return, and therefore the ground of the unit.

HENRY.—The basic unit of inductance.

HORSEPOWER.—The English unit of power, equal to work done at the rate of 550 foot-pounds per second. Equal to 746 watts of electrical power.

HYSTERESIS.—A lagging of the magnetic flux in a magnetic material behind the magnetizing force which is producing it.

IMPEDANCE.—The total opposition offered to the flow of an alternating current. It may consist of any combination of resistance, inductive reactance, and capacitive reactance.

INDUCTANCE.—The property of a circuit which tends to oppose a change in the existing current.

INDUCTION.—The act or process of producing voltage by the relative motion of a magnetic field across a conductor.

INDUCTIVE REACTANCE.—The opposition to the flow of alternating or pulsating current caused by the inductance of a circuit. It is measured in ohms.

INPHASE.—Applied to the condition that exists when two waves of the same frequency pass through their maximum and minimum values of like polarity at the same instant.

INVERSELY.—Inverted or reversed in position or relationship.

ISOGONIC LINE.—An imaginary line drawn through points on the earth's surface where the magnetic deviation is equal.

JOULE.—A unit of energy or work. A joule of energy is liberated by one ampere flowing for one second through a resistance of one ohm.

KILO.—A prefix meaning 1,000.

LAG.—The amount one wave is behind another in time; expressed in electrical degrees.

LAMINATED CORE.—A core built up from thin sheets of metal and used in transformers and relays.

LEAD.—The opposite of LAG. Also, a wire or connection.

LINE OF FORCE.—A line in an electric or magnetic field that shows the direction of the force.

LOAD.—The power that is being delivered by any power producing device. The equipment that uses the power from the power producing device.

MAGNETIC AMPLIFIER.—A saturable reactor type device that is used in a circuit to amplify or control.

MAGNETIC CIRCUIT.—The complete path of magnetic lines of force.

MAGNETIC FIELD.—The space in which a magnetic force exists.

MAGNETIC FLUX.—The total number of lines of force issuing from a pole of a magnet.

MAGNETIZE.—To convert a material into a magnet by causing the molecules to rearrange.

MAGNETO.—A generator which produces alternating current and has a permanent magnet as its field.

MEGGER.—A test instrument used to measure insulation resistance and other high resistances. It is a portable hand operated d-c generator used as an ohmmeter.

MEGOHM.—A million ohms.

MICRO.—A prefix meaning one-millionth.

MILLI.—A prefix meaning one-thousandth.

MILLIAMMETER.—An ammeter that measures current in thousandths of an ampere.

MOTOR-GENERATOR.—A motor and a generator with a common shaft used to convert line voltages to other voltages or frequencies.

MUTUAL INDUCTANCE.—A circuit property existing when the relative position of two inductors causes the magnetic lines of force from one to link with the turns of the other.

NEGATIVE CHARGE.—The electrical charge carried by a body which has an excess of electrons.

NEUTRON.—A particle having the weight of a proton but carrying no electric charge. It is located in the nucleus of an atom.

NUCLEUS.—The central part of an atom that is mainly comprised of protons and neutrons. It is the part of the atom that has the most mass.

NULL.—Zero.

OHM.—The unit of electrical resistance.

OHMMETER.—An instrument for directly measuring resistance in ohms.

OVERLOAD.—A load greater than the rated load of an electrical device.

PERMALLOY.—An alloy of nickel and iron having an abnormally high magnetic permeability.

PERMEABILITY.—A measure of the ease with which magnetic lines of force can flow through a material as compared to air.

PHASE DIFFERENCE.—The time in electrical degrees by which one wave leads or lags another.

POLARITY.—The character of having magnetic poles, or electric charges.

POLE.—The section of a magnet where the flux lines are concentrated; also where they enter and leave the magnet. An electrode of a battery.

POLYPHASE.—A circuit that utilizes more than one phase of alternating current.

POSITIVE CHARGE.—The electrical charge carried by a body which has become deficient in electrons.

POTENTIAL.—The amount of charge held by a body as compared to another point or body. Usually measured in volts.

POTENTIOMETER.—A variable voltage divider; a resistor which has a variable contact arm so that any portion of the potential applied between its ends may be selected.

POWER.—The rate of doing work or the rate of expending energy. The unit of electrical power is the watt.

POWER FACTOR.—The ratio of the actual power of an alternating or pulsating current, as measured by a wattmeter, to the apparent power, as indicated by ammeter and voltmeter readings. The power factor of an inductor, capacitor, or insulator is an expression of their losses.

PRIME MOVER.—The source of mechanical power used to drive the rotor of a generator.

PROTON.—A positively charged particle in the nucleus of an atom.

RATIO.—The value obtained by dividing one number by another, indicating their relative proportions.

REACTANCE.—The opposition offered to the flow of an alternating current by the inductance, capacitance, or both, in any circuit.

RECTIFIERS.—Devices used to change alternating current to unidirectional current. These may be vacuum tubes, semiconductors such as germanium and silicon, and dry-disk rectifiers such as selenium and copper-oxide.

RELAY.—An electromechanical switching device that can be used as a remote control.

RELUCTANCE.—A measure of the opposition that a material offers to magnetic lines of force.

RESISTANCE.—The opposition to the flow of current caused by the nature and physical dimensions of a conductor.

RESISTOR.—A circuit element whose chief characteristic is resistance; used to oppose the flow of current.

RETENTIVITY.–The measure of the ability of a material to hold its magnetism.

RHEOSTAT.–A variable resistor.

SATURABLE REACTOR.–A control device that uses a small d-c current to control a large a-c current by controlling core flux density.

SATURATION.–The condition existing in any circuit when an increase in the driving signal produces no further change in the resultant effect.

SELF-INDUCTION.–The process by which a circuit induces an e.m.f. into itself by its own magnetic field.

SERIES-WOUND.–A motor or generator in which the armature is wired in series with the field winding.

SERVO.–A device used to convert a small movement into one of greater movement or force.

SERVOMECHANISM.–A closed-loop system that produces a force to position an object in accordance with the information that originates at the input.

SOLENOID.–An electromagnetic coil that contains a movable plunger.

SPACE CHARGE.–The cloud of electrons existing in the space between the cathode and plate in a vacuum tube, formed by the electrons emitted from the cathode in excess of those immediately attracted to the plate.

SPECIFIC GRAVITY–The ratio between the density of a substance and that of pure water, at a given temperature.

SYNCHROSCOPE–An instrument used to indicate a difference in frequency between two a-c sources.

SYNCHRO SYSTEM.–An electrical system that gives remote indications or control by means of self-synchronizing motors.

TACHOMETER.–An instrument for indicating revolutions per minute.

TERTIARY WINDING.–A third winding on a transformer or magnetic amplifier that is used as a second control winding.

THERMISTOR.–A resistor that is used to compensate for temperature variations in a circuit.

THERMOCOUPLE.–A junction of two dissimilar metals that produces a voltage when heated.

TORQUE.–The turning effort or twist which a shaft sustains when transmitting power.

TRANSFORMER.–A device composed of two or more coils, linked by magnetic lines of force, used to transfer energy from one circuit to another.

TRANSMISSION LINES.–Any conductor or system of conductors used to carry electrical energy from its source to a load.

VARS.–Abbreviation for volt-ampere, reactive.

VECTOR.–A line used to represent both direction and magnitude.

VOLT.–The unit of electrical potential.

VOLTMETER.–An instrument designed to measure a difference in electrical potential, in volts.

WATT.–The unit of electrical power.

WATTMETER.–An instrument for measuring electrical power in watts.

Formulas

Ohm's Law for d-c Circuits

$$I = \frac{E}{R} = \frac{P}{E} = \sqrt{\frac{P}{R}}$$

$$R = \frac{E}{I} = \frac{P}{I^2} = \frac{E^2}{P}$$

$$E = IR = \frac{P}{I} = \sqrt{PR}$$

$$P = EI = \frac{E^2}{R} = I^2 R$$

Resistors in Series

$$R_T = R_1 + R_2 \ldots$$

Resistors in Parallel
Two resistors

$$R_T = \frac{R_1 R_2}{R_1 + R_2}$$

More than two

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

Appendix V — ELECTRICAL TERMS AND FORMULAS

R-L Circuit Time Constant equals

$$\frac{\text{L (in henrys)}}{\text{R (in ohms)}} = \text{t (in seconds), or}$$

$$\frac{\text{L (in microhenrys)}}{\text{R (in ohms)}} = \text{t (in microseconds)}$$

R-C Circuit Time Constants equals

R (ohms) X C (farads) = t (seconds)
R (megohms) x C (microfarads) = t (seconds)
R (ohms) x C (microfarads) = t (microseconds)
R (megohms) x C (micromicrofrads = t (microseconds)

Comparison of Units in Electric and Magnetic Circuits.

	Electric circuit	Magnetic circuit
Force	Volt, E or e.m.f.	Gilberts, F, or m.m.f.
Flow	Ampere, I	Flux, Φ, in maxwells
Opposition	Ohms, R	Reluctance, R
Law	Ohm's law, $I = \frac{E}{R}$	Rowland's law $\Phi = \frac{F}{R}$
Intensity of force	Volts per cm. of length	$H = \frac{1.257IN}{L}$, gilberts per centimeter of length
Density	Current density—for example, amperes per cm^2.	Flux density—for example, lines per cm^2., or gausses

Capacitors in Series

Two capacitors

$$C_T = \frac{C_1 C_2}{C_1 + C_2}$$

More than two

$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \ldots$$

Capacitors in Parallel

$$C_T = C_1 + C_2 \ldots$$

Capacitive Reactance

$$X_c = \frac{1}{2\pi fC}$$

Impedance in an R-C Circuit (Series)

$$Z = \sqrt{R^2 + X_c{}^2}$$

Inductors in Series

$$L_T = L_1 + L_2 \ldots \text{ (No coupling between coils)}$$

Inductors in Parallel

Two inductors

$$L_T = \frac{L_1 L_2}{L_1 + L_2} \text{ (No coupling between coils)}$$

More than two

$$\frac{1}{L_T} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} \ldots \text{ (No coupling between coils)}$$

Inductive Reactance

$$X_L = 2\pi fL$$

Q of a Coil

$$Q = \frac{X_L}{R}$$

Impedance of an R-L Circuit (series)

$$Z = \sqrt{R^2 + X_L^2}$$

Impedance with R, C, and L in Series

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

Parallel Circuit Impedance

$$Z = \frac{Z_1 Z_2}{Z_1 + Z_2}$$

Sine-Wave Voltage Relationships

Average value

$$E_{\text{ave}} = \frac{2}{\pi} \times E_{\text{max}} = 0.637 E_{\text{max}}$$

BASIC ELECTRICITY

Effective or r.m.s. value

$$E_{eff} = \frac{E_{max}}{\sqrt{2}} = \frac{E_{max}}{1.414} = 0.707E_{max} = 1.11E_{ave}$$

Maximum value

$$E_{max} = \sqrt{2}E_{eff} = 1.414E_{eff} = 1.57E_{ave}$$

Voltage in an a-c circuit

$$E = IZ = \frac{P}{I \times P.F.}$$

Current in an a-c circuit

$$I = \frac{E}{Z} = \frac{P}{E \times P.F.}$$

Power in A-C Circuit

Apparent power $= EI$

True power

$$P = EI \cos \theta = EI \times P.F.$$

Power factor

$$P.F. = \frac{P}{EI} = \cos \theta$$

$$\cos \theta = \frac{\text{true power}}{\text{apparent power}}$$

Transformers

Voltage relationship

$$\frac{E}{E} = \frac{N}{N} \text{ or } E = E \times \frac{N}{N}$$

Current relationship

$$\frac{I_p}{I_s} = \frac{N_s}{N_p}$$

Induced voltage

$$E_{eff} = 4.44\, BAfN 10^{-8}$$

Turns ratio equals

$$\frac{N_P}{N_s} = \sqrt{\frac{Z_P}{Z_s}}$$

Secondary current

$$I_s = I_P \frac{N_P}{N_s}$$

Secondary voltage

$$E_s = E_P \frac{N_s}{N_P}$$

Three Phase Voltage and Current Relationships

With wye connected windings

$$E_{line} = 1.732E_{coil} = \sqrt{3}E_{coil}$$

$$I_{line} = I_{coil}$$

With delta connected windings

$$E_{line} = E_{coil}$$

$$I_{line} = 1.732I_{coil}$$

With wye or delta connected winding

$$P_{coil} = E_{coil}I_{coil}$$

$$P_t = 3P_{coil}$$

$$P_t = 1.732E_{line}I_{line}$$

(To convert to true power multiply by cos θ)

Synchronous Speed of Motor

$$\text{r.p.m.} = \frac{120 \times \text{frequency}}{\text{number of poles}}$$

APPENDIX VI
TRIGONOMETRIC FUNCTIONS

In a right triangle, there are several relationships which always hold true. These relationships pertain to the length of the sides of a right triangle, and the way the lengths are affected by the angles between them. An understanding of these relationships, called trigonometric functions, is essential for solving many problems in a-c circuits such as power factor, impedance, voltage drops, and so forth.

To be a RIGHT triangle, a triangle must have a "square" corner; one in which there is exactly 90° between two of the sides. Trigonometric functions do not apply to any other type of triangle. This type of triangle is shown in figure VI-1.

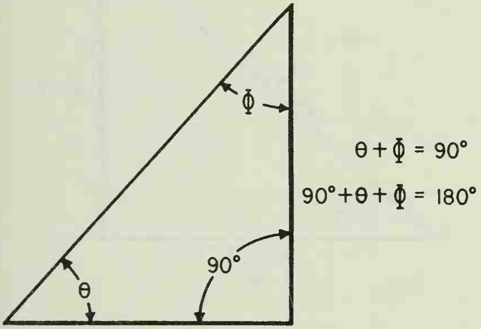


Figure VI-1.—A right triangle.

By use of the trigonometric functions, it is possible to determine the UNKNOWN length of one or more sides of a triangle, or the number of degrees in UNKNOWN angles, depending on what is presently known about the triangle. For instance, if the lengths of any two sides are known, the third side and both angles θ (theta) and Φ (phi) may be determined. The triangle may also be solved if the length of any one side and one of the angles (θ or Φ in fig. VI-I) are known.

The first basic fact to accept, regarding triangles, is that IN ANY TRIANGLE, THE SUM OF THE THREE ANGLES FORMED INSIDE THE TRIANGLE MUST ALWAYS EQUAL 180°. If one angle is always 90° (a right angle) then the sum of the other two angles must always be 90°.

$$\theta + \Phi = 90^\circ$$

and $$90^\circ + \theta + \Phi = 180^\circ$$

or $$90^\circ + 90^\circ = 180^\circ$$

thus, if angle θ is known, Φ may be quickly determined.

For instance, if θ is 30°, what is Φ ?

$$90^\circ + 30^\circ + \Phi = 180^\circ$$

Transposing $$\Phi = 180^\circ - 90^\circ - 30^\circ$$

$$\Phi = 60^\circ$$

Also, if Φ is known, θ may be determined in the same manner.

The second basic fact you must understand is that FOR EVERY DIFFERENT COMBINATION OF ANGLES IN A TRIANGLE, THERE IS A DEFINITE RATIO BETWEEN THE LENGTHS OF THE THREE SIDES. Consider the triangle in figure VI-2, consisting of the base, side B; the altitude, side A; and the hypotenuse, side C. (The hypotenuse is always the longest side, and is always opposite the 90° angle.) If angle θ is 30°, Φ must be 60°. With θ equal to 30°, the ratio of the length of side B to side C is 0.866 to 1. That is, if the hypotenuse is 1 inch long, the side adjacent to θ , side B, is 0.866 inch long. Also, with θ equal to 30°, the ratio of side A to side C is 0.5 to 1. That is, with the hypotenuse 1 inch long, the side opposite to θ (side A) is 0.5 inch long. With θ still at 30°, side A is 0.5774 of the length of B. With the combination of angles given (30° - 60° - 90°) these are the ONLY ratios of lengths that will "fit" to form a right triangle.

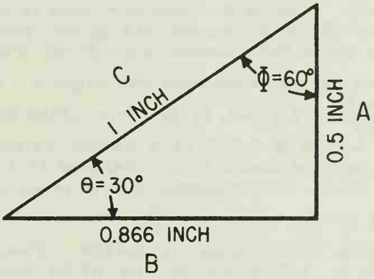


Figure VI-2.—A 30° - 60° - 90° triangle.

Note that three ratios are shown to exist for the given value of θ : the ratio $\frac{B}{C}$, which is always referred to as the COSINE (ratio of θ , the ratio $\frac{A}{C}$, which is always the SINE ratio of θ , and the ratio $\frac{A}{B}$, which is always the TANGENT ratio of θ . If θ changes, all three ratios change, because the lengths of the sides (base and altitude) change. There is a set of ratios for every increment between 0° and 90°. These angular ratios, or sine, cosine, and tangent functions, are listed for each degree and tenth of degree in a table at the end of this appendix. In this table, the length of the hypotenuse of a triangle is considered fixed. Thus, the ratios of length given refer to the manner in which sides A and B vary with relation to each other and in relation to side C, as angle θ is varied from 0° to 90°.

The solution of problems in trigonometry (solution of triangles) is much simpler when the table of trigonometric functions is used properly. The most common ways in which it is used will be shown by solving a series of exemplary

Problem 1: If the hypotenuse of the triangle (side C) in figure VI-3(A) is 10 inches long, and angle θ is 33°, how long are sides B and A? Solution: The ratio $\frac{B}{C}$ is the cosine function. By checking the table of functions, you will find that the cosine of 33° is 0.8387. This means that the length of B is 0.8387 the length of side C. If side C is 10 inches long, then side B must be 10 x 0.8387, or 8.387 inches in length. To determine the length of side A, use the sine function, the ratio $\frac{A}{C}$. Again consulting the table of functions, you will find that the sine of 33° is 0.5446. Thus, side A must be 10 x 0.5446, or 5.446 inches in length.

Problem 2: The triangle in figure VI-3 (B) has a base 74.2 feet long, and a hypotenuse 100 feet long. What is θ, and how long is side A? Solution: When no angles are given, you must always solve for a known angle first. The ratio $\frac{B}{C}$ is the cosine of the unknown angle θ; therefore $\frac{74.2}{100}$, or 0.742, is the cosine of the unknown angle. Locating 0.742 as a cosine value in the table, you find that it is the cosine of 42.1°. That is, $\theta =$ 42.1°. With θ known, side A is solved for by use of the sine ratio $\frac{A}{C}$. The sine of 42.1°, according to the table, is 0.6704. Therefore, side A is 100 x 0.6704, or 67.04 feet long.

Problem 3: In the triangle in figure VI-3 (C), the base is 3 units long, and the altitude is 4 units. What is θ, and how long is the hypotenuse? Solution: With the information given, the tangent of θ may be determined. $\tan\theta = \frac{A}{B} = \frac{4}{3} = 1.33$ Locating the value 1.33 as a tangent value in the table of functions, you find it to be the tangent of 53.2°. Therefore, θ = 53.2°. Once θ is known, either the sine or cosine ratio may be used to determine the length of the hypotenuse. The cosine of 53.2° is 0.6004. This indicates that the

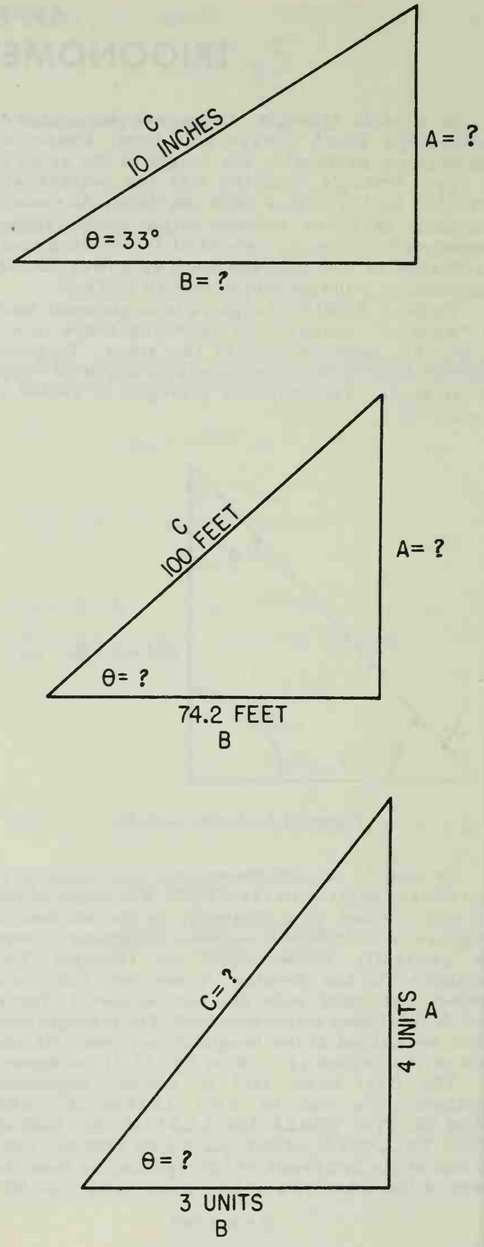


Figure VI-3.—Trigonometric problems.

base of 3 units is 0.6004, the length of the hypotenuse. Therefore, the hypotenuse is $\frac{3}{0.6004}$, or 5 units in length. Using the sine ratio, the hypotenuse is $\frac{4}{0.7997}$, or 5 units in length.

In the foregoing explanations and problems, the sides of triangles were given in inches, feet, and units. In applying trigonometry to a-c circuit problems, these units of measure will be replaced by such measurements as ohms, amperes, volts, and watts. Angle θ will often be referred to as the phase angle. However, the solution of these a-c problems is accomplished in exactly the same manner as the foregoing problems. Only the units and some terminology are changed.

NATURAL SINES, COSINES, AND TANGENTS

0° - 14.9°

Degs.	Function	0.0°	0.1°	0.2°	0.3°	0.4°	0.5°	0.6°	0.7°	0.8°	0.9°
0	sin	0.0000	0.0017	0.0035	0.0052	0.0070	0.0087	0.0105	0.0122	0.0140	0.0157
	cos	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999	0.9999	0.9999	0.9999
	tan	0.0000	0.0017	0.0035	0.0052	0.0070	0.0087	0.0105	0.0122	0.0140	0.0157
1	sin	0.0175	0.0192	0.0209	0.0227	0.0244	0.0262	0.0279	0.0297	0.0314	0.0332
	cos	0.9998	0.9998	0.9998	0.9997	0.9997	0.9997	0.9996	0.9996	0.9995	0.9995
	tan	0.0175	0.0192	0.0209	0.0227	0.0244	0.0262	0.0279	0.0297	0.0314	0.0332
2	sin	0.0349	0.0366	0.0384	0.0401	0.0419	0.0436	0.0454	0.0471	0.0488	0.0506
	cos	0.9994	0.9993	0.9993	0.9992	0.9991	0.9990	0.9990	0.9989	0.9988	0.9987
	tan	0.0349	0.0367	0.0384	0.0402	0.0419	0.0437	0.0454	0.0472	0.0489	0.0507
3	sin	0.0523	0.0541	0.0558	0.0576	0.0593	0.0610	0.0628	0.0645	0.0663	0.0680
	cos	0.9986	0.9985	0.9984	0.9983	0.9982	0.9981	0.9980	0.9979	0.9978	0.9977
	tan	0.0524	0.0542	0.0559	0.0577	0.0594	0.0612	0.0629	0.0647	0.0664	0.0682
4	sin	0.0698	0.0715	0.0732	0.0750	0.0767	0.0785	0.0802	0.0819	0.0837	0.0854
	cos	0.9976	0.9974	0.9973	0.9972	0.9971	0.9969	0.9968	0.9966	0.9965	0.9963
	tan	0.0699	0.0717	0.0734	0.0752	0.0769	0.0787	0.0805	0.0822	0.0840	0.0857
5	sin	0.0872	0.0889	0.0906	0.0924	0.0941	0.0958	0.0976	0.0993	0.1011	0.1028
	cos	0.9962	0.9960	0.9959	0.9957	0.9956	0.9954	0.9952	0.9951	0.9949	0.9947
	tan	0.0875	0.0802	0.0910	0.0928	0.0945	0.0963	0.0981	0.0998	0.1016	0.1033
6	sin	0.1045	0.1063	0.1080	0.1097	0.1115	0.1132	0.1149	0.1167	0.1184	0.1201
	cos	0.9945	0.9943	0.9942	0.9940	0.9938	0.9936	0.9934	0.9932	0.9930	0.9928
	tan	0.1051	0.1069	0.1086	0.1104	0.1122	0.1139	0.1157	0.1175	0.1192	0.1210
7	sin	0.1219	0.1236	0.1253	0.1271	0.1288	0.1305	0.1323	0.1340	0.1357	0.1374
	cos	0.9925	0.9923	0.9921	0.9919	0.9917	0.9914	0.9912	0.9910	0.9907	0.9905
	tan	0.1228	0.1246	0.1263	0.1281	0.1299	0.1317	0.1334	0.1352	0.1370	0.1388
8	sin	0.1392	0.1409	0.1426	0.1444	0.1461	0.1478	0.1495	0.1513	0.1530	0.1547
	cos	0.9903	0.9900	0.9898	0.9895	0.9893	0.9890	0.9888	0.9885	0.9882	0.9880
	tan	0.1405	0.1423	0.1441	0.1459	0.1477	0.1495	0.1512	0.1530	0.1548	0.1566
9	sin	0.1564	0.1582	0.1599	0.1616	0.1633	0.1650	0.1668	0.1685	0.1702	0.1719
	cos	0.9877	0.9874	0.9871	0.9869	0.9866	0.9863	0.9860	0.9857	0.9854	0.9851
	tan	0.1584	0.1602	0.1620	0.1638	0.1655	0.1673	0.1691	0.1709	0.1727	0.1745
10	sin	0.1736	0.1754	0.1771	0.1788	0.1805	0.1822	0.1840	0.1857	0.1874	0.1891
	cos	0.9848	0.9845	0.9842	0.9839	0.9836	0.9833	0.9829	0.9826	0.9823	0.9820
	tan	0.1763	0.1781	0.1799	0.1817	0.1835	0.1853	0.1871	0.1890	0.1908	0.1926
11	sin	0.1908	0.1925	0.1942	0.1959	0.1977	0.1994	0.2011	0.2028	0.2045	0.2062
	cos	0.9816	0.9813	0.9810	0.9806	0.9803	0.9799	0.9796	0.9792	0.9789	0.9785
	tan	0.1944	0.1962	0.1980	0.1998	0.2016	0.2035	0.2053	0.2071	0.2089	0.2107
12	sin	0.2079	0.2096	0.2113	0.2130	0.2147	0.2164	0.2181	0.2198	0.2215	0.2232
	cos	0.9781	0.9778	0.9774	0.9770	0.9767	0.9763	0.9759	0.9755	0.9751	0.9748
	tan	0.2126	0.2144	0.2162	0.2180	0.2199	0.2217	0.2235	0.2254	0.2272	0.2290
13	sin	0.2250	0.2267	0.2284	0.2300	0.2318	0.2334	0.2351	0.2368	0.2385	0.2402
	cos	0.9744	0.9740	0.9736	0.9732	0.9728	0.9724	0.9720	0.9715	0.9711	0.9707
	tan	0.2309	0.2327	0.2345	0.2364	0.2382	0.2401	0.2419	0.2438	0.2456	0.2475
14	sin	0.2419	0.2436	0.2453	0.2470	0.2487	0.2504	0.2521	0.2538	0.2554	0.2571
	cos	0.9703	0.9699	0.9694	0.9690	0.9686	0.9681	0.9677	0.9673	0.9668	0.9664
	tan	0.2493	0.2512	0.2530	0.2549	0.2568	0.2586	0.2605	0.2623	0.2642	0.2661
Degs.	Function	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′

Appendix VI – TRIGONOMETRIC FUNCTIONS

NATURAL SINES, COSINES, AND TANGENTS

15° - 29.9°

Degs.	Function	0.0°	0.1°	0.2°	0.3°	0.4°	0.5°	0.6°	0.7°	0.8°	0.9°
15	sin	0.2588	0.2605	0.2622	0.2639	0.2656	0.2672	0.2689	0.2706	0.2723	0.2740
	cos	0.9659	0.9655	0.9650	0.9646	0.9641	0.9636	0.9632	0.9627	0.9622	0.9617
	tan	0.2679	0.2698	0.2717	0.2736	0.2754	0.2773	0.2792	0.2811	0.2830	0.2849
16	sin	0.2756	0.2773	0.2790	0.2807	0.2823	0.2840	0.2857	0.2874	0.2890	0.2907
	cos	0.9613	0.9608	0.9603	0.9598	0.9593	0.9588	0.9583	0.9578	0.9573	0.9568
	tan	0.2867	0.2886	0.2905	0.2924	0.2943	0.2962	0.2981	0.3000	0.3019	0.3038
17	sin	0.2924	0.2940	0.2957	0.2974	0.2990	0.3007	0.3024	0.3040	0.3057	0.3074
	cos	0.9563	0.9558	0.9553	0.9548	0.9542	0.9537	0.9532	0.9527	0.9521	0.9516
	tan	0.3057	0.3076	0.3096	0.3115	0.3134	0.3153	0.3172	0.3191	0.3211	0.3230
18	sin	0.3090	0.3107	0.3123	0.3140	0.3156	0.3173	0.3190	0.3206	0.3223	0.3239
	cos	0.9511	0.9505	0.9500	0.9494	0.9489	0.9483	0.9478	0.9472	0.9466	0.9461
	tan	0.3249	0.3269	0.3288	0.3307	0.3327	0.3346	0.3365	0.3385	0.3404	0.3424
19	sin	0.3256	0.3272	0.3289	0.3305	0.3322	0.3338	0.3355	0.3371	0.3387	0.3404
	cos	0.9455	0.9449	0.9444	0.9438	0.9432	0.9426	0.9421	0.9415	0.9409	0.9403
	tan	0.3443	0.3463	0.3482	0.3502	0.3522	0.3541	0.3561	0.3581	0.3600	0.3620
20	sin	0.3420	0.3437	0.3453	0.3469	0.3486	0.3502	0.3518	0.3535	0.3551	0.3567
	cos	0.9397	0.9391	0.9385	0.9379	0.9373	0.9367	0.9361	0.9354	0.9348	0.9342
	tan	0.3640	0.3659	0.3679	0.3699	0.3719	0.3739	0.3750	0.3779	0.3799	0.3819
21	sin	0.3584	0.3600	0.3616	0.3633	0.3649	0.3665	0.3681	0.3697	0.3714	0.3730
	cos	0.9336	0.9330	0.9323	0.9317	0.9311	0.9304	0.9298	0.9291	0.9285	0.9278
	tan	0.3839	0.3859	0.3879	0.3899	0.3919	0.3939	0.3959	0.3979	0.4000	0.4020
22	sin	0.3746	0.3762	0.3778	0.3795	0.3811	0.3827	0.3843	0.3859	0.3875	0.3891
	cos	0.9272	0.9265	0.9259	0.9252	0.9245	0.9239	0.9232	0.9225	0.9219	0.9212
	tan	0.4040	0.4061	0.4081	0.4101	0.4122	0.4142	0.4163	0.4183	0.4204	0.4224
23	sin	0.3907	0.3923	0.3939	0.3955	0.3971	0.3987	0.4003	0.4019	0.4035	0.4051
	cos	0.9205	0.9198	0.9191	0.9184	0.9178	0.9171	0.9164	0.9157	0.9150	0.9143
	tan	0.4245	0.4265	0.4286	0.4307	0.4327	0.4348	0.4369	0.4390	0.4411	0.4431
24	sin	0.4067	0.4083	0.4099	0.4115	0.4131	0.4147	0.4163	0.4179	0.4195	0.4210
	cos	0.9135	0.9128	0.9121	0.9114	0.9107	0.9100	0.9092	0.9085	0.9078	0.9070
	tan	0.4452	0.4473	0.4494	0.4515	0.4536	0.4557	0.4578	0.4599	0.4621	0.4642
25	sin	0.4226	0.4242	0.4258	0.4274	0.4289	0.4305	0.4321	0.4337	0.4352	0.4368
	cos	0.9063	0.9056	0.9048	0.9041	0.9033	0.9026	0.9018	0.9011	0.9003	0.8996
	tan	0.4663	0.4684	0.4706	0.4727	0.4748	0.4770	0.4791	0.4813	0.4834	0.4856
26	sin	0.4384	0.4399	0.4415	0.4431	0.4446	0.4462	0.4478	0.4493	0.4509	0.4524
	cos	0.8988	0.8980	0.8973	0.8965	0.8957	0.8949	0.8942	0.8934	0.8926	0.8918
	tan	0.4877	0.4899	0.4921	0.4942	0.4964	0.4986	0.5008	0.5029	0.5051	0.5073
27	sin	0.4540	0.4555	0.4571	0.4586	0.4602	0.4617	0.4633	0.4648	0.4664	0.4679
	cos	0.8910	0.8902	0.8894	0.8886	0.8878	0.8870	0.8862	0.8854	0.8846	0.8838
	tan	0.5095	0.5117	0.5139	0.5161	0.5184	0.5206	0.5228	0.5250	0.5272	0.5295
28	sin	0.4695	0.4710	0.4726	0.4741	0.4756	0.4772	0.4787	0.4802	0.4818	0.4833
	cos	0.8829	0.8821	0.8813	0.8805	0.8796	0.8788	0.8780	0.8771	0.8763	0.8755
	tan	0.5317	0.5340	0.5362	0.5384	0.5407	0.5430	0.5452	0.5475	0.5498	0.5520
29	sin	0.4848	0.4863	0.4879	0.4894	0.4909	0.4924	0.4939	0.4955	0.4970	0.4983
	cos	0.8746	0.8738	0.8729	0.8721	0.8712	0.8704	0.8695	0.8686	0.8678	0.8669
	tan	0.5543	0.5566	0.5589	0.5612	0.5635	0.5658	0.5681	0.5704	0.5727	0.5750
Degs.	Function	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′

NATURAL SINES, COSINES, AND TANGENTS

30° - 44.9°

Degs.	Function	0.0°	0.1°	0.2°	0.3°	0.4°	0.5°	0.6°	0.7°	0.8°	0.9°
30	sin	0.5000	0.5015	0.5030	0.5045	0.5060	0.5075	0.5090	0.5105	0.5120	0.5135
	cos	0.8660	0.8652	0.8643	0.8634	0.8625	0.8616	0.8607	0.8599	0.8590	0.8581
	tan	0.5774	0.5797	0.5820	0.5844	0.5867	0.5890	0.5914	0.5938	0.5961	0.5985
31	sin	0.5150	0.5165	0.5180	0.5195	0.5210	0.5225	0.5240	0.5255	0.5270	0.5284
	cos	0.8572	0.8563	0.8554	0.8545	0.8536	0.8526	0.8517	0.8508	0.8499	0.8490
	tan	0.6009	0.6032	0.6056	0.6080	0.6104	0.6128	0.6152	0.6176	0.6200	0.6224
32	sin	0.5299	0.5314	0.5329	0.5344	0.5358	0.5373	0.5388	0.5402	0.5417	0.5432
	cos	0.8480	0.8471	0.8462	0.8453	0.8443	0.8434	0.8425	0.8415	0.8406	0.8396
	tan	0.6249	0.6273	0.6297	0.6322	0.6346	0.6371	0.6395	0.6420	0.6445	0.6469
33	sin	0.5446	0.5461	0.5476	0.5490	0.5505	0.5519	0.5534	0.5548	0.5563	0.5577
	cos	0.8387	0.8377	0.8368	0.8358	0.8348	0.8339	0.8329	0.8320	0.8310	0.8300
	tan	0.6494	0.6519	0.6544	0.6569	0.6594	0.6619	0.6644	0.6669	0.6694	0.6720
34	sin	0.5592	0.5606	0.5621	0.5635	0.5650	0.5664	0.5678	0.5693	0.5707	0.5721
	cos	0.8290	0.8281	0.8271	0.8261	0.8251	0.8241	0.8231	0.8221	0.8211	0.8202
	tan	0.6745	0.6771	0.6796	0.6822	0.6847	0.6873	0.6899	0.6924	0.6950	0.6976
35	sin	0.5736	0.5750	0.5764	0.5779	0.5793	0.5807	0.5821	0.5835	0.5850	0.5864
	cos	0.8192	0.8181	0.8171	0.8161	0.8151	0.8141	0.8131	0.8121	0.8111	0.8100
	tan	0.7002	0.7028	0.7054	0.7080	0.7107	0.7133	0.7159	0.7186	0.7212	0.7239
36	sin	0.5878	0.5892	0.5906	0.5920	0.5934	0.5948	0.5962	0.5976	0.5990	0.6004
	cos	0.8090	0.8080	0.8070	0.8059	0.8049	0.8039	0.8028	0.8018	0.8007	0.7997
	tan	0.7265	0.7292	0.7319	0.7346	0.7373	0.7400	0.7427	0.7454	0.7481	0.7508
37	sin	0.6018	0.6032	0.6046	0.6060	0.6074	0.6088	0.6101	0.6115	0.6129	0.6143
	cos	0.7986	0.7976	0.7965	0.7955	0.7944	0.7934	0.7923	0.7912	0.7902	0.7891
	tan	0.7536	0.7563	0.7590	0.7618	0.7646	0.7673	0.7701	0.7729	0.7757	0.7785
38	sin	0.6157	0.6170	0.6184	0.6198	0.6211	0.6225	0.6239	0.6252	0.6266	0.6280
	cos	0.7880	0.7869	0.7859	0.7848	0.7837	0.7826	0.7815	0.7804	0.7793	0.7782
	tan	0.7813	0.7841	0.7869	0.7898	0.7926	0.7954	0.7983	0.8012	0.8040	0.8069
39	sin	0.6293	0.6307	0.6320	0.6334	0.6347	0.6361	0.6374	0.6388	0.6401	0.6414
	cos	0.7771	0.7760	0.7749	0.7738	0.7727	0.7716	0.7705	0.7694	0.7683	0.7672
	tan	0.8098	0.8127	0.8156	0.8185	0.8214	0.8243	0.8273	0.8302	0.8332	0.8361
40	sin	0.6428	0.6441	0.6455	0.6468	0.6481	0.6494	0.6508	0.6521	0.6534	0.6547
	cos	0.7660	0.7649	0.7638	0.7627	0.7615	0.7604	0.7593	0.7581	0.7570	0.7559
	tan	0.8391	0.8421	0.8451	0.8481	0.8511	0.8541	0.8571	0.8601	0.8632	0.8662
41	sin	0.6561	0.6574	0.6587	0.6600	0.6613	0.6626	0.6639	0.6652	0.6665	0.6678
	cos	0.7547	0.7536	0.7524	0.7513	0.7501	0.7490	0.7478	0.7466	0.7455	0.7443
	tan	0.8693	0.8724	0.8754	0.8785	0.8816	0.8847	0.8878	0.8910	0.8941	0.8972
42	sin	0.6691	0.6704	0.6717	0.6730	0.6743	0.6756	0.6769	0.6782	0.6794	0.6807
	cos	0.7431	0.7420	0.7408	0.7396	0.7385	0.7373	0.7361	0.7349	0.7337	0.7325
	tan	0.9004	0.9036	0.9067	0.9099	0.9131	0.9163	0.9195	0.9228	0.9260	0.9293
43	sin	0.6820	0.6833	0.6845	0.6858	0.6871	0.6884	0.6896	0.6909	0.6921	0.6934
	cos	0.7314	0.7302	0.7290	0.7278	0.7266	0.7254	0.7242	0.7230	0.7218	0.7206
	tan	0.9325	0.9358	0.9391	0.9424	0.9457	0.9490	0.9523	0.9556	0.9590	0.9623
44	sin	0.6947	0.6959	0.6972	0.6984	0.6997	0.7009	0.7022	0.7034	0.7046	0.7059
	cos	0.7193	0.7181	0.7169	0.7157	0.7145	0.7133	0.7120	0.7108	0.7096	0.7083
	tan	0.9657	0.9691	0.9725	0.9759	0.9793	0.9827	0.9861	0.9896	0.9930	0.9965
Degs.	Function	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′

Appendix VI – TRIGONOMETRIC FUNCTIONS

NATURAL SINES, COSINES, AND TANGENTS

45° - 59.9°

Degs.	Function	0.0°	0.1°	0.2°	0.3°	0.4°	0.5°	0.6°	0.7°	0.8°	0.9°
45	sin	0.7071	0.7083	0.7096	0.7108	0.7120	0.7133	0.7145	0.7157	0.7169	0.7181
	cos	0.7071	0.7059	0.7046	0.7034	0.7022	0.7009	0.6997	0.6984	0.6972	0.6959
	tan	1.0000	1.0035	1.0070	1.0105	1.0141	1.0176	1.0212	1.0247	1.0283	1.0319
46	sin	0.7193	0.7206	0.7218	0.7230	0.7242	0.7254	0.7266	0.7278	0.7290	0.7302
	cos	0.6947	0.6934	0.6921	0.6909	0.6896	0.6884	0.6871	0.6858	0.6845	0.6833
	tan	1.0355	1.0392	1.0428	1.0464	1.0501	1.0538	1.0575	1.0612	1.0649	1.0686
47	sin	0.7314	0.7325	0.7337	0.7349	0.7361	0.7373	0.7385	0.7396	0.7408	0.7420
	cos	0.6820	0.6807	0.6794	0.6782	0.6769	0.6756	0.6743	0.6730	0.6717	0.6704
	tan	1.0724	1.0761	1.0799	1.0837	1.0875	1.0913	1.0951	1.0990	1.1028	1.1067
48	sin	0.7431	0.7443	0.7455	0.7466	0.7478	0.7490	0.7501	0.7513	0.7524	0.7536
	cos	0.6691	0.6678	0.6665	0.6652	0.6639	0.6626	0.6613	0.6600	0.6587	0.6574
	tan	1.1106	1.1145	1.1184	1.1224	1.1263	1.1303	1.1343	1.1383	1.1423	1.1463
49	sin	0.7547	0.7559	0.7570	0.7581	0.7593	0.7604	0.7615	0.7627	0.7638	0.7649
	cos	0.6561	0.6547	0.6534	0.6521	0.6508	0.6494	0.6481	0.6468	0.6455	0.6441
	tan	1.1504	1.1544	1.1585	1.1626	1.1667	1.1708	1.1750	1.1792	1.1833	1.1875
50	sin	0.7660	0.7672	0.7683	0.7694	0.7705	0.7716	0.7727	0.7738	0.7749	0.7760
	cos	0.6428	0.6414	0.6401	0.6388	0.6374	0.6361	0.6347	0.6334	0.6320	0.6307
	tan	1.1918	1.1960	1.2002	1.2045	1.2088	1.2131	1.2174	1.2218	1.2261	1.2305
51	sin	0.7771	0.7782	0.7793	0.7804	0.7815	0.7826	0.7837	0.7848	0.7859	0.7869
	cos	0.6293	0.6280	0.6266	0.6252	0.6239	0.6225	0.6211	0.6198	0.6184	0.6170
	tan	1.2349	1.2393	1.2437	1.2482	1.2527	1.2572	1.2617	1.2662	1.2708	1.2753
52	sin	0.7880	0.7891	0.7902	0.7912	0.7923	0.7934	0.7944	0.7955	0.7965	0.7976
	cos	0.6157	0.6143	0.6129	0.6115	0.6101	0.6088	0.6074	0.6060	0.6046	0.6032
	tan	1.2799	1.2846	1.2892	1.2938	1.2985	1.3032	1.3079	1.3127	1.3175	1.3222
53	sin	0.7986	0.7997	0.8007	0.8018	0.8028	0.8039	0.8049	0.8059	0.8070	0.8080
	cos	0.6018	0.6004	0.5990	0.5976	0.5962	0.5948	0.5934	0.5920	0.5906	0.5892
	tan	1.3270	1.3319	1.3367	1.3416	1.3465	1.3514	1.3564	1.3613	1.3663	1.3713
54	sin	0.8090	0.8100	0.8111	0.8121	0.8131	0.8141	0.8151	0.8161	0.8171	0.8181
	cos	0.5878	0.5864	0.5850	0.5835	0.5821	0.5807	0.5793	0.5779	0.5764	0.5750
	tan	1.3764	1.3814	1.3865	1.3916	1.3968	1.4019	1.4071	1.4124	1.4176	1.4229
55	sin	0.8192	0.8202	0.8211	0.8221	0.8231	0.8241	0.8251	0.8261	0.8271	0.8281
	cos	0.5736	0.5721	0.5707	0.5693	0.5678	0.5664	0.5650	0.5635	0.5621	0.5606
	tan	1.4281	1.4335	1.4388	1.4442	1.4496	1.4550	1.4605	1.4659	1.4715	1.4770
56	sin	0.8290	0.8300	0.8310	0.8320	0.8329	0.8339	0.8348	0.8358	0.8368	0.8377
	cos	0.5592	0.5577	0.5563	0.5548	0.5534	0.5519	0.5505	0.5490	0.5476	0.5461
	tan	1.4826	1.4882	1.4938	1.4994	1.5051	1.5108	1.5166	1.5224	1.5282	1.5340
57	sin	0.8387	0.8396	0.8406	0.8415	0.8425	0.8434	0.8443	0.8453	0.8462	0.8471
	cos	0.5446	0.5432	0.5417	0.5402	0.5388	0.5373	0.5358	0.5344	0.5329	0.5314
	tan	1.5399	1.5458	1.5517	1.5577	1.5637	1.5697	1.5757	1.5818	1.5880	1.5941
58	sin	0.8480	0.8490	0.8499	0.8508	0.8517	0.8526	0.8536	0.8545	0.8551	0.8563
	cos	0.5299	0.5284	0.5270	0.5255	0.5240	0.5225	0.5210	0.5195	0.5180	0.5165
	tan	1.6003	1.6066	1.6128	1.6191	1.6255	1.6319	1.6383	1.6447	1.6512	1.6577
59	sin	0.8572	0.8581	0.8590	0.8599	0.8607	0.8616	0.8625	0.8634	0.8643	0.8652
	cos	0.5150	0.5135	0.5120	0.5105	0.5090	0.5075	0.5060	0.5045	0.5030	0.5015
	tan	1.6643	1.6709	1.6775	1.6842	1.6909	1.6977	1.7045	1.7113	1.7182	1.7251
Degs.	Function	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′

NATURAL SINES, COSINES, AND TANGENTS

60° - 74.9°

Degs.	Function	0.0°	0.1°	0.2°	0.3°	0.4°	0.5°	0.6°	0.7°	0.8°	0.9°
60	sin	0.8660	0.8669	0.8678	0.8686	0.8695	0.8704	0.8712	0.8721	0.8729	0.8738
	cos	0.5000	0.4985	0.4970	0.4955	0.4939	0.4924	0.4909	0.4894	0.4879	0.4863
	tan	1.7321	1.7391	1.7461	1.7532	1.7603	1.7675	1.7747	1.7820	1.7893	1.7966
61	sin	0.8746	0.8755	0.8763	0.8771	0.8780	0.8788	0.8796	0.8805	0.8813	0.8821
	cos	0.4848	0.4833	0.4818	0.4802	0.4787	0.4772	0.4756	0.4741	0.4726	0.4710
	tan	1.8040	1.8115	1.8190	1.8265	1.8341	1.8418	1.8495	1.8572	1.8650	1.8728
62	sin	0.8829	0.8838	0.8846	0.8854	0.8862	0.8870	0.8878	0.8886	0.8894	0.8902
	cos	0.4695	0.4679	0.4664	0.4648	0.4633	0.4617	0.4602	0.4586	0.4571	0.4555
	tan	1.8807	1.8887	1.8967	1.9047	1.9128	1.9210	1.9292	1.9375	1.9458	1.9542
63	sin	0.8910	0.8918	0.8926	0.8934	0.8942	0.8949	0.8957	0.8965	0.8973	0.8980
	cos	0.4540	0.4524	0.4509	0.4493	0.4478	0.4462	0.4446	0.4431	0.4415	0.4399
	tan	1.9626	1.9711	1.9797	1.9883	1.9970	2.0057	2.0145	2.0233	2.0323	2.0413
64	sin	0.8988	0.8996	0.9003	0.9011	0.9018	0.9026	0.9033	0.9041	0.9048	0.9056
	cos	0.4384	0.4368	0.4352	0.4337	0.4321	0.4305	0.4289	0.4274	0.4258	0.4242
	tan	2.0503	2.0594	2.0686	2.0778	2.0872	2.0965	2.1060	2.1155	2.1251	2.1348
65	sin	0.9063	0.9070	0.9078	0.9085	0.9092	0.9100	0.9107	0.9114	0.9121	0.9128
	cos	0.4226	0.4210	0.4195	0.4179	0.4163	0.4147	0.4131	0.4115	0.4099	0.4083
	tan	2.1445	2.1543	2.1642	2.1742	2.1842	2.1943	2.2045	2.2148	2.2251	2.2355
66	sin	0.9135	0.9143	0.9150	0.9157	0.9164	0.9171	0.9178	0.9184	0.9191	0.9198
	cos	0.4067	0.4051	0.4035	0.4019	0.4003	0.3987	0.3971	0.3955	0.3939	0.3923
	tan	2.2460	2.2566	2.2673	2.2781	2.2889	2.2998	2.3109	2.3220	2.3332	2.3445
67	sin	0.9205	0.9212	0.9219	0.9225	0.9232	0,9239	0.9245	0.9252	0.9259	0.9265
	cos	0.3907	0.3891	0.3875	0.3859	0.3843	0.3827	0.3811	0.3795	0.3778	0.3762
	tan	2.3559	2.3673	2.3789	2.3906	2.4023	2.4142	2.4262	2.4383	2.4504	2.4627
68	sin	0.9272	0.9278	0.9285	0.9291	0.9298	0.9304	0.9311	0.9317	0.9323	0.9330
	cos	0.3746	0.3730	0.3714	0.3697	0.3681	0.3665	0.3649	0.3633	0.3616	0.3600
	tan	2.4751	2.4876	2.5002	2.5129	2.5257	2.5386	2.5517	2.5649	2.5782	2.5916
69	sin	0.9336	0.9342	0.9348	0.9354	0.9361	0.9367	0.9373	0.9379	0.9385	0.9391
	cos	0.3584	0.3567	0.3551	0.3535	0.3518	0.3502	0.3486	0.3469	0.3453	0.3437
	tan	2.6051	2.6187	2.6325	2.6464	2.6605	2.6746	2.6889	2.7034	2.7179	2.7326
70	sin	0.9397	0.9403	0.9409	0.9415	0.9421	0.9426	0.9432	0.9438	0.9444	0.9449
	cos	0.3420	0.3404	0.3387	0.3371	0.3355	0.3338	0.3322	0.3305	0.3289	0.3272
	tan	2.7475	2.7625	2.7776	2.7929	2.8083	2.8239	2.8397	2.8556	2.8716	2.8878
71	sin	0.9455	0.9461	0.9466	0.9472	0.9478	0.9483	0.9489	0.9494	0.9500	0.9505
	cos	0.3256	0.3239	0.3223	0.3206	0.3190	0.3173	0.3156	0.3140	0.3123	0.3107
	tan	2.9042	2.9208	2.9375	2.9544	2.9714	2.9887	3.0061	3.0237	3.0415	3.0595
72	sin	0.9511	0.9516	0.9521	0.9527	0.9532	0.9537	0.9542	0.9548	0.9553	0.9558
	cos	0.3090	0.3074	0.3057	0.3040	0.3024	0.3007	0.2990	0.2974	0.2957	0.2940
	tan	3.0777	3.0961	3.1146	3.1334	3.1524	3.1716	3.1910	3.2106	3.2305	3.2506
73	sin	0.9562	0.9568	0.9573	0.9578	0.9583	0.9588	0.9593	0.9598	0.9603	0.9608
	cos	0.2924	0.2907	0.2890	0.2874	0.2857	0.2840	0.2823	0.2807	0.2790	0.2773
	tan	3.2709	3.2914	3.3122	3.3332	3.3544	3.3759	3.3977	3.4197	3.4420	3.4646
74	sin	0.9613	0.9617	0.9622	0.9627	0.9632	0.9636	0.9641	0.9646	0.9650	0.9655
	cos	0.2756	0.2740	0.2723	0.2706	0.2689	0.2672	0.2656	0.2639	0.2622	0.2605
	tan	3.4874	3.5105	3.5339	3.5576	3.5816	3.6059	3.6305	3.6554	3.6806	3.7062
Degs.	Function	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′

NATURAL SINES, COSINES, AND TANGENTS

75° - 89.9°

Degs.	Function	0.0°	0.1°	0.2°	0.3°	0.4°	0.5°	0.6°	0.7°	0.8°	0.9°
75	sin	0.9659	0.9664	0.9668	0.9673	0.9677	0.9681	0.9686	0.9690	0.9694	0.9699
	cos	0.2588	0.2571	0.2554	0.2538	0.2521	0.2504	0.2487	0.2470	0.2453	0.2436
	tan	3.7321	3.7583	3.7848	3.8118	3.8391	3.8667	3.8947	3.9232	3.9520	3.9812
76	sin	0.9703	0.9707	0.9711	0.9715	0.9720	0.9724	0.9728	0.9732	0.9736	0.9740
	cos	0.2419	0.2402	0.2385	0.2368	0.2351	0.2334	0.2317	0.2300	0.2284	0.2267
	tan	4.0108	4.0408	4.0713	4.1022	4.1335	4.1653	4.1976	4.2303	4.2635	4.2972
77	sin	0.9744	0.9748	0.9751	0.9755	0.9759	0.9763	0.9767	0.9770	0.9774	0.9778
	cos	0.2250	0.2232	0.2215	0.2198	0.2181	0.2164	0.2147	0.2130	0.2113	0.2096
	tan	4.3315	4.3662	4.4015	4.4374	4.4737	4.5107	4.5483	4.5864	4.6252	4.6646
78	sin	0.9781	0.9785	0.9789	0.9792	0.9796	0.9799	0.9803	0.9806	0.9810	0.9813
	cos	0.2079	0.2062	0.2045	0.2028	0.2011	0.1994	0.1977	0.1959	0.1942	0.1925
	tan	4.7046	4.7453	4.7867	4.8288	4.8716	4.9152	4.9594	5.0045	5.0504	5.0970
79	sin	0.9816	0.9820	0.9823	0.9826	0.9829	0.9833	0.9836	0.9839	0.9842	0.9845
	cos	0.1908	0.1891	0.1874	0.1857	0.1840	0.1822	0.1805	0.1788	0.1771	0.1754
	tan	5.1446	5.1929	5.2422	5.2924	5.3435	5.3955	5.4486	5.5026	5.5578	5.6140
80	sin	0.9848	0.9851	0.9854	0.9857	0.9860	0.9863	0.9866	0.9869	0.9871	0.9874
	cos	0.1736	0.1719	0.1702	0.1685	0.1668	0.1650	0.1633	0.1616	0.1599	0.1582
	tan	5.6713	5.7297	5.7894	5.8502	5.9124	5.9758	6.0405	6.1066	6.1742	6.2432
81	sin	0.9877	0.9880	0.9882	0.9885	0.9888	0.9890	0.9893	0.9895	0.9898	0.9900
	cos	0.1564	0.1547	0.1530	0.1513	0.1495	0.1478	0.1461	0.1444	0.1426	0.1409
	tan	6.3138	6.3859	6.4596	6.5350	6.6122	6.6912	6.7720	6.8548	6.9395	7.0264
82	sin	0.9903	0.9905	0.9907	0.9910	0.9912	0.9914	0.9917	0.9919	0.9921	0.9923
	cos	0.1392	0.1374	0.1357	0.1340	0.1323	0.1305	0.1288	0.1271	0.1253	0.1236
	tan	7.1154	7.2066	7.3002	7.3962	7.4947	7.5958	7.6996	7.8062	7.9158	8.0285
83	sin	0.9925	0.9928	0.9930	0.9932	0.9934	0.9936	0.9938	0.9940	0.9942	0.9943
	cos	0.1219	0.1201	0.1184	0.1167	0.1149	0.1132	0.1115	0.1097	0.1080	0.1063
	tan	8.1443	8.2636	8.3863	8.5126	8.6427	8.7769	8.9152	9.0579	9.2052	9.3572
84	sin	0.9945	0.9947	0.9949	0.9951	0.9952	0.9954	0.9956	0.9957	0.9959	0.9960
	cos	0.1045	0.1028	0.1011	0.0993	0.0976	0.0958	0.0941	0.0924	0.0906	0.0889
	tan	9.5144	9.6768	9.8448	10.02	10.20	10.39	10.58	10.78	10.99.	11.20
85	sin	0.9962	0.9963	0.9965	0.9966	0.9968	0.9969	0.9971	0.9972	0.9973	0.9974
	cos	0.0872	0.0854	0.0837	0.0819	0.0802	0.0785	0.0767	0.0750	0.0732	0.0715
	tan	11.43	11.66	11.91	12.16	12.43	12.71	13.00	13.30	13.62	13.95
86	sin	0.9976	0.9977	0.9978	0.9979	0.9980	0.9981	0.9982	0.9983	0.9984	0.9985
	cos	0.0698	0.0680	0.0663	0.0645	0.0628	0.0610	0.0593	0.0576	0.0558	0.0541
	tan	14.30	14.67	15.06	15.46	15.89	16.35	16.83	17.34	17.89	18.46
87	sin	0.9986	0.9987	0.9988	0.9989	0.9990	0.9990	0.9991	0.9992	0.9993	0.9993
	cos	0.0523	0.0506	0.0488	0.0471	0.0454	0.0436	0.0419	0.0401	0.0384	0.0366
	tan	19.08	19.74	20.45	21.20	22.02	22.90	23.86	24.90	26.03	27.27
88	sin	0.9994	0.9995	0.9995	0.9996	0.9996	0.9997	0.9997	0.9997	0.9998	0.9998
	cos	0.0349	0.0332	0.0314	0.0297	0.0279	0.0262	0.0244	0.0227	0.0209	0.0192
	tan	28.64	30.14	31.82	33.69	35.80	38.19	40.92	44.07	47.74	52.08
89	sin	0.9998	0.9999	0.9999	0.9999	0.9999	1.000	1.000	1.000	1.000	1.000
	cos	0.0175	0.0157	0.0140	0.0122	0.0105	0.0087	0.0070	0.0052	0.0035	0.0017
	tan	57.29	63.66	71.62	81.85	95.49	114.6	143.2	191.0	286.5	573.0
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